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UNIFIED PILOT-INDUCED OSCILLATION THEORY
VOLUME IV: TIME-DOMAIN NEAL-SMITH CRITERION

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13. ABSTRACT *(Maximum 200 words)*
This work was conducted as part of a USAF initiative to develop a comprehensive theory to predict pilot-induced oscillation (PIO) tendencies due to the combined effect of all influencing elements. A PIO is a very complicated phenomenon stemming from a dynamic interaction between the pilot and the aircraft. When tight control is required from the pilot, an undesired oscillation can result. However, the adaptive nature of the human pilot, makes such oscillations difficult to predict. This report presents the theory, fundamental principles, and analytical procedures of a quantitative criterion for the prediction of PIO tendencies in fixed-wing aircraft. The criterion is validated against three very reliable flying qualities data bases. At present, the criterion is intentionally limited to the evaluation of pitch control only. No fundamental limitations were discovered which preclude the evolution of this methodology and analytical procedures to PIO analysis of roll control or "outer-loop" longitudinal control, such as control of aircraft flight path.

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FOREWORD

A pilot-induced oscillation (PIO) results from the interaction of the pilot and the dynamics of the vehicle being controlled. It may be caused or affected by several elements of the aircraft design or the mission task. PIO affects the pilot's ability to perform a given task, ranging from an annoying aircraft motion to inability to complete the task to, in the most extreme cases, jeopardizing the safety of the aircraft and crew. Because it occurs sporadically, PIO can be one of the most insidious flying qualities problems.

Criteria currently exist for some of the elements of aircraft design which influence PIO tendencies; however, the criteria in the flying qualities standard (MIL-STD-1797) address the effect of these elements individually rather than cumulatively. These elements include sluggish response modes, low damping, excessive phase lag or time delay, overly sensitive stick gradients, unstable response modes, coupled response modes, etc. Furthermore, there are some elements that are known to influence PIO tendencies which are not addressed in MIL-STD-1797. Some examples of these elements are aerodynamic nonlinearities, control system nonlinearities, actuator rate limits, nonlinear stick gradients, etc.

This report is the first step of an Air Force initiative to develop a comprehensive and unifying theory to explain the nature of the interaction of pilot and vehicle which results in PIO and to develop the capability to predict an aircraft's PIO tendencies due to the combined effect of all influencing elements. This theory must be consistent with several PIOs which have been documented in research, development, and operational aircraft. This effort should also produce design criteria which can be used in the development process to assess the risk of PIO prior to manned simulation.

The four volumes of this report represent a broad-band approach to developing this comprehensive theory. There were five contractors involved: Calspan Corporation; Hoh Aeronautics, Inc.; McDonnell Douglas Aerospace; Systems Technology, Inc.; and Virginia Polytechnic Institute and State University. The objectives of the contractors were to develop their theories and partially validate them against existing data.

Volume I is the work of Systems Technology, Inc. This research included: compilation of available PIO time histories and references as an initial step toward a comprehensive PIO database; refinement of the proposed PIO categories defined in NASA CR-4683; development of PIO theories based on these categories; development of methods to handle the higher frequency and nonlinear aspects of PIO analysis with an emphasis on rate limiting; and a review of existing and proposed linear PIO criteria.

Volume II is the combined work of McDonnell Douglas Aerospace, Advanced Transport Aircraft at Long Beach, CA, McDonnell Douglas Aerospace, Advanced Programs, at St. Louis, MO, and Hoh Aeronautics, Inc. at Lomita, CA. There are primarily two components associated with this study. One element is an examination of PIO events that have occurred in the course of initial flight development on several aircraft produced by

the McDonnell Douglas Corporation. The other element is an exploration of several theories associated with PIOs, particularly those with rate limiting involved.

Volume III was produced by the Virginia Tech Department of Aerospace and Ocean Engineering. This report describes an analysis method capable of predicting PIO tendencies due to several simultaneous factors. A unified approach involving pilot modeling, stability robustness analysis, and multivariable describing function analysis is applied to the problem of identifying aircraft with PIO tendencies. The approach is shown to have ties to existing PIO criteria and is successfully applied to the prediction of PIO tendencies of the M2-F2 lifting body.

Volume IV is the result of Calspan's efforts. This report presents the theory, fundamental principles, and analytical procedures of a quantitative criterion for the prediction of PIO tendencies based on a "time-domain Neal-Smith" approach. The criterion is validated against three very reliable flying qualities data bases. At present the criterion is intentionally limited to the evaluation of pitch control only. No fundamental limitations were discovered which preclude the evolution of this methodology and analytical procedures to PIO analysis of roll control or "outer-loop" longitudinal control, such as control of aircraft flight path.

After further evaluation and deliberation of these reports, the Air Force will pursue the most promising ideas, or combination of ideas, and validate them with further simulation and flight testing.

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ACKNOWLEDGMENTS

This report presents the final results from the development of a quantitative criterion for the prediction of Pilot-Induced Oscillation (PIO) tendencies in fixed-wing aircraft. This work was conducted under Task Number 94-21 of the USAF NT-33/TIFS/VISTA In-Flight Simulator Operations contract (Contract No. F33615-C-3608). The USAF Program Manager for this contract is Mr. Steve Markman and the Calspan Program Manager is Mr. Louis H. Knotts.

This work was conducted as part of the USAF initiative for the development of a Unified PIO Theory. Mr. Dave Leggett is the program manager for this USAF initiative and served as the technical monitor for this effort. Mr. Randall E. Bailey was the principal investigator for Calspan with the assistance of Mr. Timothy J. Bidlack. Technical computing assistance was provided by Mr. James L. Lyons. Mr. Charles R. Chalk served as the expert consultant on this effort and provided, as always, great insight into the analysis of PIO and the prediction of PIO tendencies. Mike Parrag is gratefully acknowledged for his thorough and knowledgeable editorial review of this work.

This report is organized by following an outline provided by the USAF. Consequently, some sections of the report will contain little, if any information. Also, the logical flow of the report may not be as smooth as it could be. The intention of the following the USAF outline is to facilitate USAF efforts in combining the reports of the Unified PIO Theory contractors into a single summary report. Thus, a lack of information under some report sections reflects the absence of effort or attention in that section under this effort. (The "missing" information was addressed by one or several of the other contractors).

ACRONYMS AND ABBREVIATIONS

$\lvert\theta/\theta_c\rvert_{max}$	Maximum Closed-Loop Resonance
$(\dot{\ })$	Rate of Change with Respect to Time, d( )/dt
s	Laplace Operation
D	Acquisition Time, sec
dB	decibels
deg	degrees
δ_{es}	Pitch Stick Position
KIAS	Knots, Indicated Air Speed
K_p	Pilot Compensator Gain
LAHOS	Landing Approach High Order System
$\angle_{pc}$	Phase Angle, deg, of Pilot Compensator at Bandwidth Frequency
M(x)	Median Value of x
msec	milliseconds
N-S	Neal-Smith
PIO	Pilot-Induced Oscillation
PIOR	Pilot-Induced Oscillation Rating
PR	Pilot Rating
θ	Pitch Attitude
θ_c	Pitch attitude Command
θ_e	Pitch Attitude Error, $= \theta_c - \theta$
rad	radians
rms	root mean squared
STT	Step Target Tracking
TBD	To Be Determined
TIFS	Total In-Flight Simulator
T_L	Pilot Compensator Lead Time Constant (Lead Compensator Model)
TOT	Time-On-Target
t_{p_1}	Pilot Compensator Lead Time Constant (Lead-Lag Compensation Model)
t_{p_2}	Pilot Compensator Lag Time Constant (Lead-Lag Compensator Model)
USAF	United States Air Force
ω_{BW}	Bandwidth frequency, rad/sec

Section 1.0
INTRODUCTION

A. Scope

This report presents the final results from the development of a quantitative criterion for the prediction of Pilot-Induced Oscillation (PIO) tendencies in fixed-wing aircraft.

The theory, fundamental principles, and analytical procedures for a quantitative PIO criterion are presented in the following sections. This criterion is validated against three very reliable flying qualities data bases. The results are very encouraging and, as shown by comparison to the three databases, excellent discrimination of PIO is obtained.

At present, the criterion was intentionally limited to the evaluation of pitch control only. Resource limitations did not afford a complete validation or criterion development. This limitation can be easily removed and a "fully-developed and validated" criterion can be put in place once additional resources are available. No fundamental limitations were discovered which preclude the evolution of this methodology and analytical procedures for PIO analysis of roll control or "outer-loop" longitudinal control, such as control of aircraft flight path.

B. Objectives

Several objectives were undertaken in this work:

1) The proposed criterion is intended to fill the "PIO gap" in the current flying qualities Mil-Standard by providing an analytical tool which has direct correlation to PIO tendencies and pilot-in-the-loop flying qualities evaluations.

2) The methodology is developed in the time domain to contrast the majority of current criterion which reside in the frequency domain. The new methodology will, thus, differ from the current criteria in that it will not be restricted or hindered in the analysis of nonlinear control laws by linearity assumptions or by a priori assumptions of pilot inputs or control activity.

3) The criterion will provide an aide to bridge the transition from flying qualities specification, design, and analysis through to pilot-in-the-loop testing. Therefore, the proposed criterion will nicely complement the

planned addition of flight test maneuver requirements into the Mil-Standard.

C. Plan

In this report, detailed background is presented for the reader to grasp the genesis of this criterion and its basis in established flying qualities principles. Following this background, very brief remarks are given in Section 3 under "PIO theory" to highlight how this criterion relates to the theory of PIO. Details of this criterion and its development are given in Section 4 ("PIO Analysis").

Section 2.0
BACKGROUND

A. Unified PIO Criteria Development

An Air Force initiative was started to modify the current aircraft flying qualities military standard (MIL-STD-1797) to include quantitative Pilot-Induced Oscillation (PIO) criteria. This modification was a consequence of the PIO briefing (Reference 1) that was given to General Yates, commander of the Air Force Air Materiel Command, following the YF-22 accident (Reference 2). From this briefing, the lack of quantitative PIO criteria was felt to be a deficiency in the specification and subsequent design of digital aircraft flight control systems. Unfortunately, very few sound quantitative PIO criteria exist; MIL-STD-1797 is a reflection of this fact.

Revisions to MIL-STD-1797 are also planned to incorporate precisely defined piloting tasks which will be used as the final "proof" of satisfactory flying qualities characteristics and hence, compliance with the intent of the MIL-Standard.

A.1 MIL-STD-1797 Design Criteria

MIL-STD-1797 precludes the acceptance of PIO in a design (in §4.1.11.6) by requiring that "There shall be no tendency for pilot-induced oscillations, that is, sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft." Essentially this same subjective requirement is repeated in the roll and yaw axis-related requirements in §4.5.2 ("Pilot-induced Roll Oscillations") and §4.6.3 ("Pilot-induced Yaw Oscillations"). The quantitative PIO criteria included in MIL-STD-1797 are *inferred* from §4.1.11.6 by reference to the specific requirements of §4.2.1.2 ("Short Term Pitch Response") and §4.2.2 (Pilot-induced Pitch Oscillations").

In the pitch axis section of MIL-STD-1797, the "Pilot-induced Pitch Oscillation" requirement (§4.2.2) contains a qualitative and quantitative requirement. The qualitative requirement portion "restricts" abrupt changes in pitch response characteristics which may induce PIO tendencies. The quantitative portion of the requirement places limits in the allowable phase lag between the pilot control input and the aircraft's subsequent normal acceleration response. This numerical requirement is based on the work published in AFFDL-TR-77-57 (the so-called "Ralph Smith criterion," Reference 3). Although substantiation of the Ralph Smith criterion can be found (e.g., Reference 4), others have found the criterion to be a poor indicator of PIO potential (e.g.,

Reference 5). In addition, the criterion suffers from the same deficiencies that plague other frequency domain-based "PIO criteria," as demonstrated in the following.

The "Short Term Pitch Response" requirement (§4.2.1.2), as opposed to the "Pilot-induced Pitch Oscillation" requirement (§4.2.2), contains the vast majority of the available fly-by-wire design requirements for pitch flying qualities and hence, pitch PIO requirements. The Mil-Standard format permits the use of several alternate criteria to demonstrate design compliance with this requirement, including the equivalent systems approach (Reference 6), the "Bandwidth" criterion (Reference 7), a modified Neal-Smith criterion (Reference 8), and Gibson's design guidelines (Reference 9). These requirements, rather than the Ralph Smith criterion, were the primary, viable quantitative PIO criteria available at the time of MIL-STD-1797 publication; however, they were not specifically "advertised" for this purpose per se and thus, were not always viewed by the aircraft manufacturers or USAF System Program Office (SPO) engineers as explicit PIO criteria. Thus, PIO-prone or susceptible designs could slip through Mil-Standard requirements if the guidance of these criteria were somehow ignored or disregarded (Reference 1).

A.2 MIL-STD-1797 Limitations

It has been demonstrated (e.g., Reference 4 and 5) that PIO tendencies during control of an aircraft pitch response are predicted with reasonable accuracy using the requirements of the current Mil-Standard, particularly from the criteria of the Short Term Pitch Response requirements (§4.2.1.2). An apparent deduction would be that PIO can indeed be identified and eliminated from a design by just enforcing the current requirements. While this is true to a large extent, several fundamental deficiencies in the MIL-STD-1797 requirements do exist, nonetheless. These deficiencies were "known" by many people actively involved in flying qualities research and development, but unfortunately, they were vividly exposed to a wider audience by several aircraft incidences of PIO. These PIO experiences prompted the digital flight control systems review conducted by the Air Force (Reference 1) which concluded that:

- The Mil-Standard short period requirements are often ignored in the design process.

  Numerous assumptions are implied or invoked in demonstrating compliance or in designing to Mil-Standard requirements. These assumptions and associated limitations can negate the applicability of the

aforementioned flying qualities/PIO criteria. The result may be that the criteria are often effectively ignored in the design.

- The Mil-Standard doesn't require practical "proof" of a PIO-free design.

  Requirements are being drafted for MIL-STD-1797 inclusion which will dictate flight test validation of the flying qualities design.

- Explicit, not implied, quantitative PIO criteria are needed.

  The current requirements do not explicitly state that the pitch requirements actually serve as PIO criteria. The one criteria that does advertise to predict PIO is ineffective. Without explicit requirements, PIO prevention cannot be ensured.

A.3 Proposed PIO Criteria Basis

These limitations of the Mil-Standard are recognized and the quantitative PIO criterion, developed herein, is cognizant of these deficiencies and attempts to mitigate them.

One of the most prominent assumptions invoked in the Short Period Response requirement is linearity. This assumption is not directly made in the requirements nor is it *required* in demonstrating compliance with the Mil-Standard, but this assumption is often used. For instance, in generating frequency response data to test a design against frequency domain criteria, linear analysis methods are often used to compute transfer function response characteristics. Even though methods are available to "detect" or test for nonlinearity in this process, linearity will be invoked exclusively to show Mil-Standard criteria compliance. These assumptions can produce misleading or erroneous results.

Describing function analysis is another method to map the effects of nonlinearities into the frequency domain. Unfortunately, describing function analysis requires a priori assumptions of the inputs to the nonlinearities. This assumption means that the pilot control inputs or control activity has to be known or assumed. This assumption is not usually valid until after pilot-in-the-loop testing is completed and even then, it may not be accurate.

In today's aircraft flight control system design, nonlinearities are littered throughout a control law design to task-tailor an aircraft's response. Nonlinearities are essential in providing

superior flying qualities characteristics. Design requirements which penalize nonlinearities are counter-productive.

Ironically, nonlinearities have been cited as one of the primary causes of PIO (Reference 10). Intentionally-designed nonlinearities are introduced for predictable, virtuous response characteristics to pilot inputs or external disturbances whereas, unintentional (PIO-producing) nonlinearities create unpredictable, deleterious response characteristics. Intentional or not, nonlinearity is a fact that must be dealt with in a control law design and in its analysis. The assumption of linearity underlying the PIO requirements of the Mil-Standard detract from their utility and, consequently, the requirements are often ignored.

In addition to assumptions on linearity, the available Mil-Standard criteria differ in many respects such as their "applicability." The criteria are not, by any means, fool-proof nor validated for all possible design circumstances. Sufficiency in the flying qualities design cannot be guaranteed by analysis and design requirements only. Pilot-in-the-loop simulation is a necessity. Simulation should be relied upon - but not exclusively - to evaluate the flying qualities design and PIO tendencies. Good design practice utilizes requirements, analysis, and simulation for guidance, development, test, and evaluation (Reference 11) in a complementary fashion.

More fundamental than the assumptions that detract from the effectiveness of the available Mil-Standard PIO criteria, however, is their exclusion of the key ingredient in the PIO problem - the pilot. Without the pilot entering the control loop, pilot-induced oscillations are not possible. The pilot does not create a PIO, rather the problem is resident in the vehicle which the pilot is attempting to control to attain the task performance demanded of the pilot-vehicle dynamic system. Flying qualities are, in essence, the definition of the pilot's ability to achieve this performance and the ease (workload) with which this performance is attained (Reference 12). To some extent, the modified Neal-Smith criterion allowed in the Short Term Pitch Response requirement (§4.2.1.2) addresses this deficiency.

A.4 Quantitative PIO Criterion Objectives

The intent of this quantitative PIO criterion development is not to replace the existing Short Period Response requirements (§4.2.1.2), but rather, to augment these tested, well-known criteria/requirements with a "true" PIO test. The proposed PIO criterion would replace the current Pilot-induced Pitch Oscillations requirement (§4.2.1.2) with a "measurement" for PIO potential that would not be subjected to the "assumptions" explicitly stated or implied in the other

requirements; therefore, this requirement would introduce a test of sufficiency in the flying qualities design by not invoking assumptions, such as linearity, and most importantly, by incorporating the "pilot" in the loop. In addition, the criterion will hold analogies with piloted evaluation techniques so that a transition from paper design to pilot-in-the-loop simulation and flight test will be available by using this criterion. This criterion will, thus, complement the planned addition of flight test demonstration into MIL-STD-1797 and bridge the gap which would otherwise exist between the existing Mil-Standard requirements and the new flight test requirements.

The criterion is based on pilot-in-the-loop analysis but does not require an explicit modeling of the pilot. The proposed criterion includes a "pilot" only in the sense that control of the vehicle is a closed-loop process. The "pilot" element in the criterion is a simple compensator. The premise, invoked with this criterion, is analogous to that of the Neal-Smith criterion (Reference 8): If good closed-loop control can be attained with a very simple compensator serving as the "pilot," then a fully adaptive human pilot can certainly achieve that same level of performance or better.

The "pilot" element (i.e., compensator) in the pilot-vehicle model provides a closed-loop test for the flying qualities design. No attempt is made here to identify or empirically establish the characteristics of the proposed "pilot" compensator other than to reference that its basis is fundamentally sound as shown from the results of previous pilot modeling studies.

A.5 PIO Criterion Development

The proposed criterion is based significantly on the work of the:

- Neal-Smith criterion (Reference 8); and,
- "Step Target Tracking Criterion" (Reference 13).

Each of these criteria have been shown to be good discriminators of pitch flying qualities, but deficiencies in their applicability have also been cited (e.g., Reference 5). The effort performed under this contract identified remedies to these known deficiencies and developed a criterion in accordance with the aforementioned objectives.

A.6 Extension to the Neal-Smith Criterion

The Neal-Smith criterion was originally developed from the observations and results of an in-flight investigation of longitudinal fighter aircraft flying qualities performing precision pitch tracking. The criterion is formulated by modeling the pilot-airplane control loop as a unity feedback system with a pilot model of an assumed form in the forward path. In its original application, the pitch attitude control loop was modeled (Figure 1). Modifications of this model for lateral-directional flying qualities analysis have also been made (e.g., Reference 14 and 15).

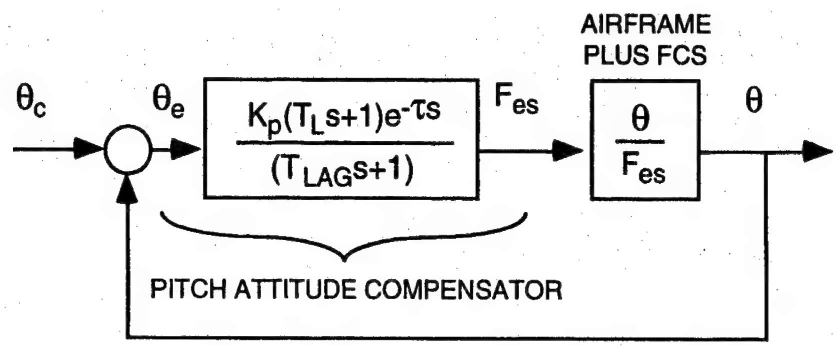


Figure 1: Neal-Smith Criterion Pilot-Vehicle Control Model

The assumed pilot model form accounts for the observed characteristics of pilots when controlling dynamic systems. The pilot model form incorporates:

- Adjustable gain.
- Time delay.
- Ability to develop lead compensation.
- Ability to develop lag compensation.
- Ability to provide low frequency integration (not shown in Figure 1).

Since the above pilot model was not experimentally confirmed, the pilot element of the proposed criterion is termed a pitch attitude compensator. It should be emphasized, however, that it is not necessary for this simple pilot model to be an exact analog of the human pilot for the criterion to be a valid flying qualities "test."

The criterion assumes that, for a given mission/task, the pilot imposes a standard of task performance or degree of aggressiveness in closing the control loop. This performance standard is measured in the frequency domain by the closed-loop bandwidth frequency (ω_{BW}). The bandwidth requirement is task-dependent and has been determined from correlation of available pilot ratings. The closed-loop performance is further constrained by limiting low frequency "droop." This constraint ensures that steady-state tracking performance cannot be sacrificed at the expense of achieving the closed-loop bandwidth requirements (Figure 2).

The criterion output parameters are the phase angle of the required pilot compensation measured at the bandwidth frequency, $\angle_{pc}$, and the maximum closed-loop resonance, $|\theta/\theta_c|_{max}$ (Figure 2). The pilot compensation roughly quantifies the pilot workload and the closed-loop resonance gauges the closed-loop dynamic performance or stability as the resonance relates to the damping of the closed-loop system and is considered a measure of PIO potential.

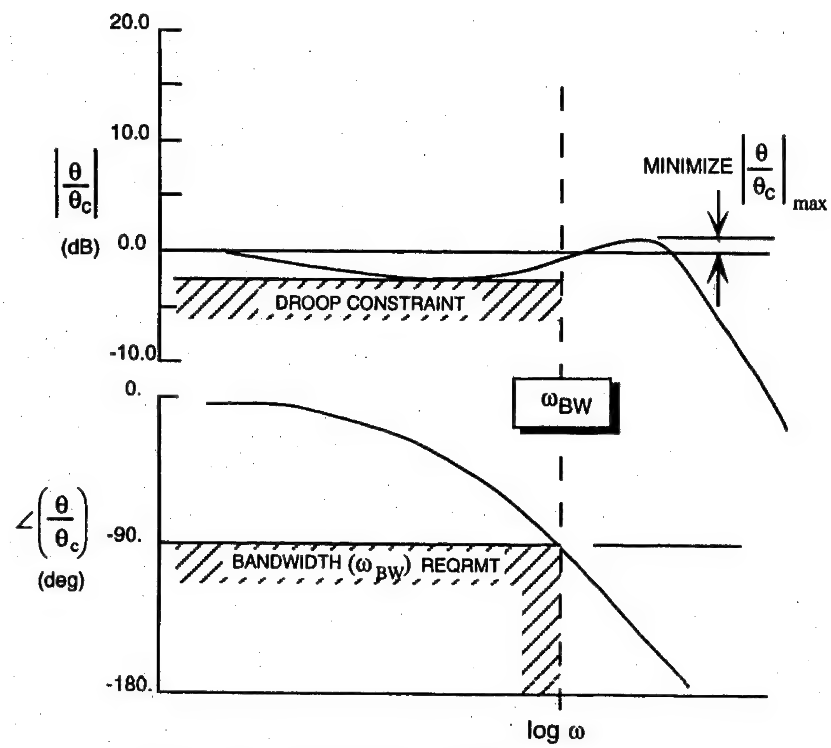


Figure 2: Neal-Smith Criterion Constraints

Flying qualities are essentially defined as the ease and precision with which closed-loop pilot-vehicle system performance is achieved (Reference 12). Using the Neal-Smith criterion, flying qualities are evaluated by plotting the output values of pilot phase compensation, $\angle_{pc}$, and maximum closed-loop resonance, $|\theta/\theta_c|_{max}$, on the Neal-Smith parameter plane. Thus, the

precision with which the demanded task performance is attained is related to the bandwidth required for the task and the closed-loop system damping (i.e., resonance, $|\theta/\theta_c|_{max}$, of the closed-loop system). The ease with which the pilot was able to achieve this level of performance is related to the pilot compensation, $\angle_{pc}$ (i.e., a significant component of pilot workload), used to achieve this task performance. Typical pilot comments associated with the Neal-Smith parameter plane and associated flying qualities boundaries are sketched in Figure 3.

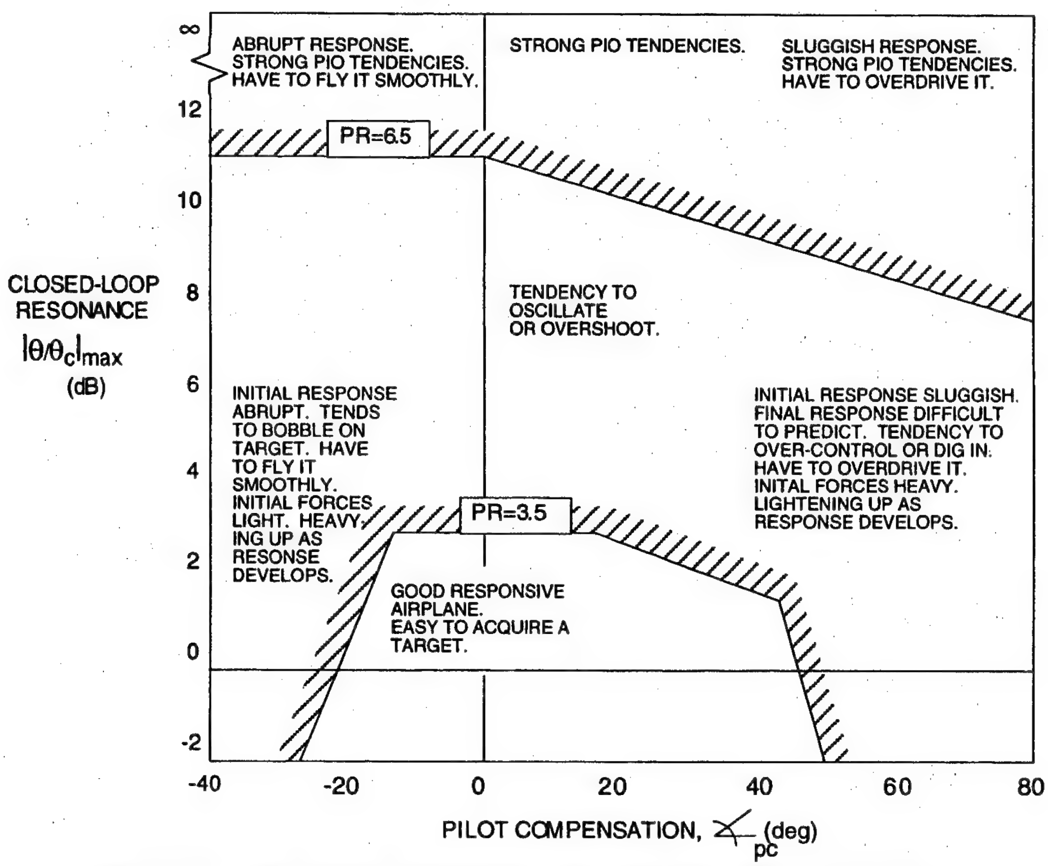


Figure 3: Neal-Smith Parameter Plane/Typical Pilot Comments

The Neal-Smith criterion provides an excellent flying qualities metric under two conditions:

1) The criterion is based on the premise that satisfactory pitch flying qualities are a necessary, but perhaps not sufficient, prerequisite to good longitudinal flying qualities.

2) The criterion is strictly an evaluation of the dynamic response characteristics; the criterion pilot model can use infinite as well as

infinitesimal gain (K_p) to satisfy the closed-loop dynamic response requirements. The presumption is that the criterion will guide the definition of the short period dynamic response characteristics. The command gain, however, must also be designed within limits appropriate to the task and the controller.

A form of the Neal-Smith criterion is included in the MIL-STD-1797 pitch flying qualities dynamic response requirements (§4.2.1.2). The bandwidth requirements are given as:

- Flight Phase Category A tasks: ω_{BW} = 3.5 rad/sec
- Flight Phase Category B tasks: ω_{BW} = 1.5 rad/sec
- Landing (Flight Phase Category C) task: ω_{BW} = 2.5 rad/sec
- Other Flight Phase Category C tasks: ω_{BW} = 1.5 rad/sec

A fixed value of pilot time delay of 0.25 sec is required by MIL-STD-1797 for use in the pitch attitude compensator model.

More importantly than as a "static" flying qualities requirement, however, the framework of the Neal-Smith criterion mimics the pilot-vehicle closed-loop system and thus, can be used as a test of PIO tendency. This PIO test can be made through adjustment of the pilot loop-closure parameters of the Neal-Smith criterion model - the task bandwidth and/or pilot time delay. These loop-closure parameters correlate with the task demands, pilot aggressiveness, and/or changes in pilot control technique. Variations in their values will simulate, with this very simple pilot model, the sensitivity of a configuration to these known PIO "trigger mechanisms." Thus, a quantitative measure of PIO tendency is offered.

This criterion parameter variation has been used informally in the past to quantify the PIO sensitivity of a configuration by mapping the results in the Neal-Smith parameter plane. Roughly, it has been shown that a configuration with poor flying qualities (i.e., a PIO-prone configuration) will show very large increases in closed-loop resonance and/or require large increases in pilot compensation as the task demands increase (i.e., higher bandwidth) or the pilot time delay increases (i.e., "impaired" or imperfect pilot control technique). For a good configuration, little change to the closed-loop parameters is generally exhibited with these same loop-closure changes. These trends are shown for two configurations from Reference 8 in Figure 4. The good configuration, Configuration 2d, exhibits little movement through the parameter plane

as the task bandwidth increases from 1.5 rad/sec to 3.5 rad/sec. Conversely, the "bad" configuration, Configuration 6e, moves rapidly through the parameter plane for the same change in task performance demands. Flying qualities and PIO tendencies are correlated to this parametric sensitivity.

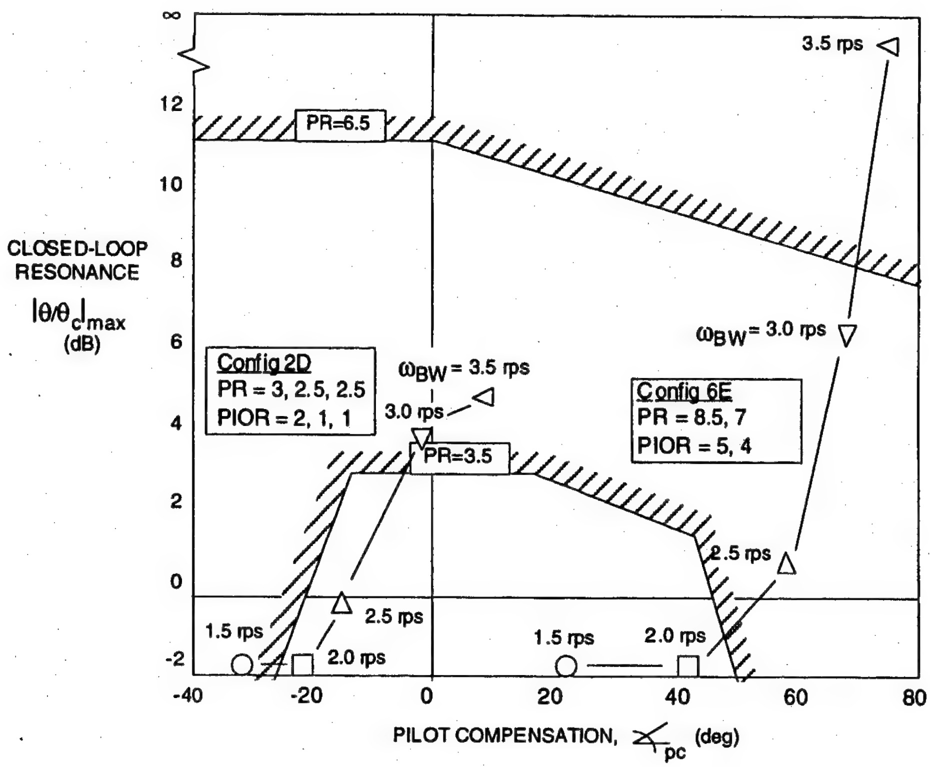


Figure 4: Mapping of Two Configurations with Bandwidth Requirement Changes

In Reference 5, criteria were proposed based on correlation trends apparent in the data. The term, "adaptability," was used to label the proposed criteria since the variation of these parameters roughly demonstrated how adaptable the pilot-vehicle system was in the face of task or pilot control technique changes. The adaptability criteria were proposed as a complement or even, another dimension to the "static" correlation of a configuration against the Neal-Smith parameter plane. The proposed adaptability criteria were developed from carpet plot maps of the variation of the pilot-vehicle response to Neal-Smith model changes. The plots in Figure 4 show the closed-loop resonance that results from meeting a given bandwidth requirement with a given pilot time delay value (τ_p) and the attendant pilot compensation (using the pilot lead time constant, T_L, = ω_{BW} tan($\angle_{pc}$) as this measure). From these carpet plots, good and poor flying qualities could be roughly distinguished by their "sensitivity." Configurations that were insensitive to task or pilot control changes tended to exhibit superior flying qualities as opposed to PIO-prone configurations

that exhibited significant variation in closed-loop resonance with task or pilot compensation changes.

The proposed adaptability criteria were essentially derivative terms (i.e., the rate of change of one variable with respect to another) reflecting the sensitivity of a configuration in the Neal-Smith criterion. As derivative terms, they are complementary in nature to the "static" correlation obtained using the Neal-Smith criterion parameter plane for a single bandwidth frequency (ω_{BW}).

The proposed adaptability criteria have also been used as explanations of why configurations of different flying qualities ratings lie in the same general area of the parameter plane in a "static" Neal-Smith criterion (Reference 5) and why some configurations exhibit relatively large scatter in pilot ratings (Reference 16). For instance, large flying qualities and hence, pilot rating differences may occur for configurations with high sensitivity to the Neal-Smith criterion output parameters reflecting that a configuration's flying qualities change significantly for relatively small task or pilot compensation changes (i.e., high values of the adaptability criteria).

A.7 Step Target Tracking (STT) Criterion

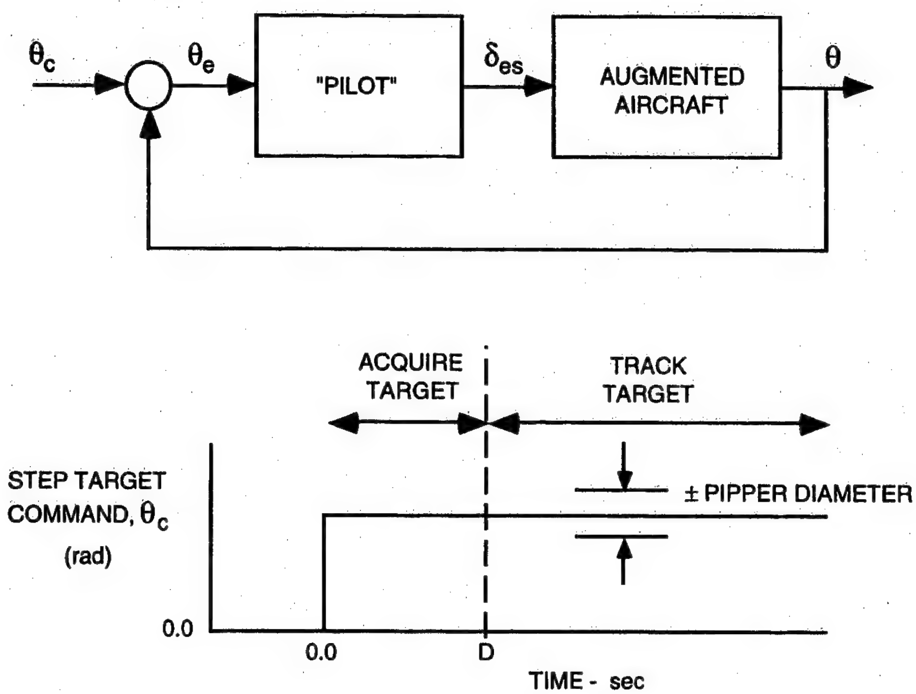
The other significant work on which the PIO criterion in this report was based is the Step Target Tracking (STT) criterion developed by Onstott et al (Reference 13).

The STT criterion holds many analogies with the frequency domain-based Neal-Smith criterion. First and foremost, the method uses a simple pilot model as a "test" of the pitch dynamic response characteristics. Thus, an excellent basis for pitch PIO evaluation is offered. A pilot loop closure of pitch attitude is modeled (Figure 5). Again, the presumption is that satisfactory pitch dynamic response characteristics are a necessary, but perhaps not sufficient, prerequisite to good longitudinal flying qualities.

A bi-modal pilot model in the STT criterion is assumed. In the time-domain based criterion, the tracking task and the attendant pilot model is initially in a target acquisition mode until some time, D, when the task and pilot model switches to a target tracking mode. The "acquisition" pilot model utilizes pitch attitude error (θ_e) and pitch attitude rate error ($\dot{\theta}_e$) in the compensatory model. The "tracking" pilot model uses pitch attitude error, pitch attitude rate error, and integral

pitch attitude error ($\int \theta_e$). Adjustable gain and a time delay are modeled in both phases. The pilot is assumed to attempt rapid initial target acquisition and precise final tracking. A 5 second time period is used in the criterion.

In the original criterion development, a step target command in pitch attitude (θ_c) is used as a target tracking test (Figure 5). Optimization is employed to compute the pilot model parameters which maximize the Time-On-Target (TOT). (TOT is the cumulative time for which the pitch attitude is within one pipper diameter of the pitch attitude command.)



ACQUISITION

$$\text{TIME<D,} \quad \delta_{es}\Big|_i = (\text{DELAY } \tau)\ \{K_{p_i}(\theta_e(t) + T_{L_i}\dot{\theta}_e(t))\}$$

TRACKING

$$\text{TIME} \geq \text{D,} \quad \delta_{es}\Big|_f = (\text{DELAY } \tau)\ \{K_{p_f}(\theta_e(t) + T_{L_f}\dot{\theta}_e(t) + K_{I_f}\int_0^t \theta_e(w)dw)\}$$

Figure 5: Step Target Tracking Model (Reference 13)

The optimization procedure in the original criterion requires the selection of the optimal values for the pilot model, as well as the switching time, D, in which the pilot (actually the pitch attitude compensator) transitions from the target acquisition phase to the target tracking phase. The switching time, D, is defined as the time at which the pitch attitude (θ) was 80% of the command (θ_c). This time is determined using the acquisition pilot model adjusted to obtain rapid acquisition of the target with moderate overshoot and oscillation.

Good discrimination of the Neal-Smith experiment data base flying qualities results was shown in Reference 13 by plotting the TOT against the rms θ_e for each configuration. In this parameter plane (Figure 6), good flying qualities were related to configurations with high time-on-target (TOT) and low rms pitch error (rms θ_e)values. These measures intuitively correlate to good target tracking performance (i.e., good closed-loop pilot-vehicle dynamic system performance) since the pilot-vehicle combination can presumably achieve good steady-state performance (high TOT) with rapid acquisition yet with minimum overshoot or oscillation (low rms error). Conversely, low TOT and high rms θ_e values correlate to poor performance and PIO tendencies.

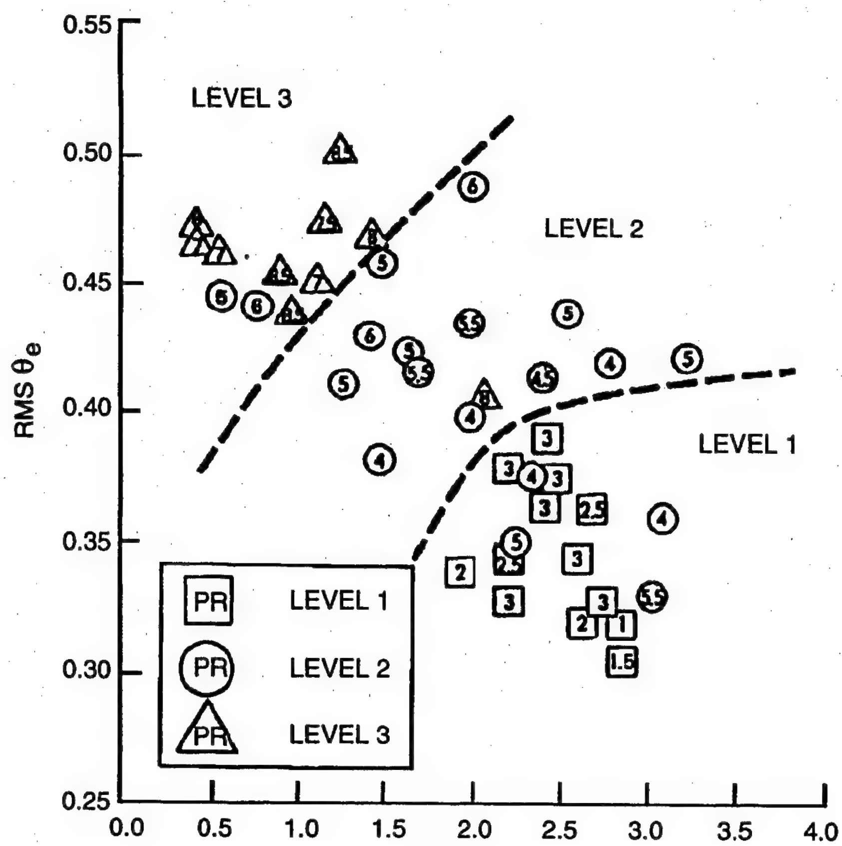


Figure 6: Original Step Target Tracking Criterion

In Reference 5, an analysis of the STT criterion was made. This analysis revealed many advantages to the criterion and its methods; however, some shortcomings in the criterion were also shown:

- Excellent discrimination of the Neal-Smith data base was shown in Reference 13. However, some distortions are present because some data, considered to be invalid by the authors of the Reference 8 data base, were included in the criterion development shown in Figure 6. Also, some simplifications in the computation of the criterion were invoked. Together, these factors distorted the correlation of the criterion to the data of Reference 8. In Reference 5, a brief re-evaluation the criterion indicated that the criterion had merit and warranted further examination.

- The switching time, D, is essentially a measure of the system bandwidth. If the pilot adopts compensation to achieve a (K/s) open-loop response, the closed-loop time domain response of this system for a unity step command input is $\theta(t) = 1.0 - e^{-Kt}$. The time to reach the tracking model switching time, D, is found by solving this equation for the time to reach 80% of the pitch attitude command (Reference 13). This equation:

  $$D = t(\theta = 0.8\theta_c) = -(1.0/K)\ln(1.0 - 0.80)$$

  shows that the switching time is inversely proportional to the bandwidth, K, of this "ideal" system.

- One major deficiency of the criterion is the lack of a workload or pilot compensation measure. The criterion is currently composed of only performance measures (i.e., TOT and rms θ_e); flying qualities definition requires both performance and pilot compensation/workload metrics.

A.8 PIO Development Summary

The effort to develop a quantitative PIO criteria closely followed the original Step Target Tracking criterion with modifications and amplifications extracted from the Neal-Smith criterion work. The general intent was to provide a criterion which is as worthy and capable as the Neal-Smith criterion yet be based in the time-domain so that the incorporation and treatment of nonlinearities becomes a trivial issue.

In essence, this quantitative PIO metric is created through the development of a Time Domain Neal-Smith criterion.

Section 3.0
PIO THEORY

A. Definitions

The PIO criterion work, documented herein, was not an examination of PIO theory, per se, but rather, was the development of a metric by which an augmented aircraft configuration can be analyzed to assess whether the potential for PIO exists. Thus, new definitions of PIO or contributions to PIO theory were not directly part of this work.

B. Acceptable/Unacceptable Characteristics

The Time Domain Neal-Smith criterion is developed herein and validated against three very reliable flying qualities data bases. To the extent that these data bases cover the gamut of acceptable and unacceptable aircraft characteristics, the developed criterion is valid.

The PIO criterion, in its present state, is limited to the analysis of pitch control only. An initial hypothesis is that this criterion is a necessary but perhaps not sufficient prerequisite for good longitudinal flying qualities. No limitations have been found to date which would restrict expanding the scope of coverage by this criterion and eliminating this assumption. This work is proposed for a follow-on effort.

C. Causes

PIO can be caused by linear and/or nonlinear characteristics of the augmented aircraft. Because of the formulation of the proposed PIO criterion in the time domain, approximation or describing function analysis of nonlinear elements is not necessary and they can be modeled without simplification.

C.1 Linear

The ability of the Time Domain Neal-Smith criterion to successfully identify PIO potential due to linear effects is demonstrated by analysis of the Neal-Smith data base (Reference 8), the Landing Approach High Order System (LAHOS) data base (Reference 17), and the TIFS Pitch Rate program data base (Reference 18). In each of these data bases, linear aerodynamic and flight control system characterization is valid.

The primary "linear" cause of PIO contained in these three data bases is phase lag introduced between the pilot control stick input and the subsequent aircraft response. The phase lag created effective or equivalent delay between the pilot's stick input and the aircraft response. These lags were produced by second-order and/or first-order flight control system prefilters (hence, the moniker, high order systems).

The other linear cause of PIO which was evident in the TIFS data is a dynamic disharmony or disassociation between the pitch attitude and flight path responses due to flight control system prefilter dynamics or augmentation. Since the pilot uses the aircraft pitch response as a cue to gauge the flight path response, this disharmony or disassociation created an unpredictable aircraft flight path response

C.2 Nonlinear

The treatment of nonlinear PIO causes should be the area where the proposed criterion excels in comparison to frequency-domain or linear-based criteria. Unfortunately, the data base with which to validate the criterion for nonlinear causes (and identification of its effects) is limited and was not directly part of this development work.

Instead, nonlinear PIO effects are analyzed by using several hypothetical examples. The examples were those of a rate-limited actuator which presumably will create a PIO scenario. The analysis and PIO metric are applied to these examples.

Trigger events are not presumed nor theorized. A trigger event is assumed to occur at some point; it's cause or type is immaterial to the proposed PIO criterion.

The criterion assumes that a trigger event <u>will</u> occur at some point in time and the subsequent PIO tendencies will be gauged by the proposed pilot-in-the-loop criterion. The criterion uses a PIO "forcing function" which is essentially a hypothetical trigger event. The forcing function is the variation in the task performance demanded of the pilot-vehicle system.

Section 4.0
PIO ANALYSIS PROCESS

A. Process Outline

The process of PIO analysis using the developed method begins with a mathematical model of the aircraft and flight control system (i.e., the "augmented aircraft"). This description is written in the time domain with pilot stick inputs and aircraft state outputs being defined for the analysis. The aircraft state outputs should be referenced to the pilot station since a pilot-in-the-loop test is defined.

The augmented aircraft representation (i.e., the aerodynamics, control laws, and equations of motion) is contained in the simulation package in the "augmented aircraft" block shown in the schematic diagram in Figure 7. The PIO analysis is an algorithm which calls the simulation package; control of the augmented aircraft is produced by the algorithm using a simple pilot compensator model to produce pilot control inputs in response to a step command in pitch attitude (θ_c). The algorithm (and attendant analysis procedure) is an optimization problem which determines the "pilot compensator" which produces optimal pilot-vehicle performance based upon defined "flying qualities" rules governing the problem. The compensator mimics pilot closed-loop control behavior for the pitch attitude tracking task.

This work is the initial development of a quantitative PIO test. Although significant work has been performed, the current, validated development is limited to pitch control only. Subsequent efforts will be directed for roll control and longitudinal outer-loop control (e.g., flight path control). As the subsequent sections show, excellent correlation is produced for the pitch-only control situation and no hindrances were apparent which would prohibit extending the criterion to these other "axes."

Flying qualities "measures" are deduced from the analytical results and quantitative measures of PIO are proposed. A flying qualities criterion (as opposed to the specific development objective of producing a PIO metric) was developed to serve primarily as a sanity check and to provide a foundation for the PIO metric. The flying qualities criterion ingredients relate to the closed-loop pilot-vehicle performance and pilot compensation to achieve this performance. These ingredients are necessitated by the basic definition of flying qualities (Reference 12). (It is assumed in this analysis that pilot compensation directly and significantly creates pilot workload. Other factors that may produce pilot workload are not considered in this analysis (Reference 19)).

PIO tendencies are gauged by the variation in the flying qualities measures as a function of required task or closed-loop performance changes imposed upon the "pilot." The performance or task demands are an integral feature of the closed-loop model and PIO test. They should be considered to be the inputs to the PIO-tendency test. The PIO test outputs are the closed-loop performance and pilot compensation (workload) measures which are cast into a PIO-tendency criterion.

The pilot-in-the-loop criterion is not intended to be an analog of the pilot-vehicle system nor a precise analytical modeling of the actual pilot-vehicle closed-loop system. The closed-loop modeling process is utilized as a test; it is assumed that if good performance can be attained with this simple compensator, then certainly as good or better performance can be expected under actual pilot control.

Although it is not an analog of the pilot-vehicle closed-loop system, the closed-loop model can still be a very useful and valuable tool to analyze actual simulation or flight test data. The proposed analytical model can provide a "baseline" from which to compare and analyze the actual data. The algorithm provides a relatively simple pilot model and associated engineering measures (as part of this PIO test) which can be compared to actual piloting task data. For instance, a pilot in a simulation may utilize a highly nonlinear adaptive control technique to attain a certain level of tracking task performance. This nonlinear technique will clearly be exposed by time domain comparison of the actual data to the simple closed-loop time domain analysis proposed herein (e.g., comparison of control input activity and resultant tracking performance).

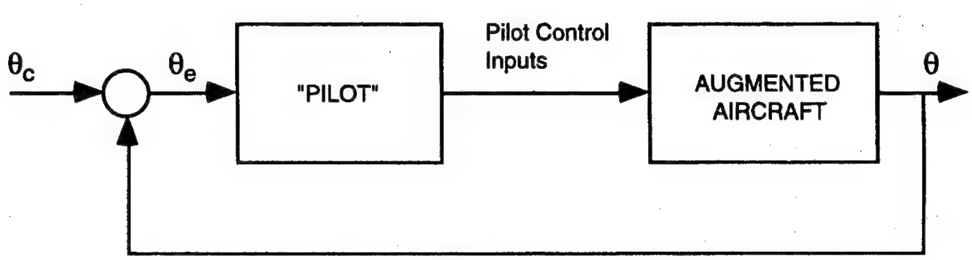


Figure 7: Closed-Loop Pitch Attitude Task Schematic Diagram

B. Open-Loop Analyses

Open-loop analysis is not an integral part of this quantitative PIO test. It is, however, complementary to this analysis or for that matter to any flying qualities analysis or specification. By using both open-loop and closed-loop analyses, insight into the configuration PIO tendencies

and the causes of PIO can be gained which otherwise might not be obtained from analysis using one exclusive of the other.

C. Closed-Loop Analyses

The closed-loop analysis procedures are outlined below. First, however, the criterion development history is documented since significant insight into the PIO analysis procedures can be gained from understanding its development.

C.1 PIO Criterion Development

The original Frequency Domain Neal-Smith and Onstott's time domain STT criterion were integral to the criterion development. The starting point in the criterion's development was Onstott's STT work, but the STT criterion was modified significantly to approach a time domain Neal-Smith criterion-equivalent.

C.2 Tracking Task Definition

The tracking task definition which serves as the basis for the Time Domain Neal-Smith criterion development was not significantly changed from Onstott's STT work.

The foundation of the criterion is the computation of the closed-loop pitch attitude control task over a 5.0 sec period. A step pitch attitude command (θ_C) of 5.0 degrees, going in at 0.25 sec, was assumed. Different pitch attitude commands were not evaluated in this development.

The step pitch attitude command was centered at 0.25 sec. The command was equal to: 2.5 degrees (one-half the full-scale command value) at 0.25 sec; and, 5.0 degrees at t=(0.25 + dt) seconds. The term, dt, is the computational time interval (in sec) of the time domain simulation.

The step command occurs at 0.25 sec (as opposed to 0.00 sec) to ensure that initial conditions would not be a hidden influence in the PIO analysis formulation. The analysis is, however, sensitive to the pitch step command definition. This sensitivity is a consequence of pilot lead compensation which means that the pilot control inputs are a function of the step attitude command rate term (i.e., $\dot{\theta}_e = \dot{\theta}_c - \dot{\theta}$). Relatively minor changes in the step command description will produce significantly different time history results for the same pilot model and augmented

aircraft. The "sloped" input command documented above appears to be a reasonable input and, if the command "convention" is maintained, numerical similarity in computing the PIO analysis will not be a problem or factor.

Continuous integration using a Runge-Kutta integration algorithm was used for the time domain simulation. Some discrete simulations were conducted for numerical checks and comparable results were obtained given the aforementioned step input command description caveats.

The tracking task input description requires the definition of a pipper error. This pipper error is physically related to the definition of an acceptable tracking error. In terms of the Cooper-Harper rating scale, this pipper error should be the definition of the desired task performance for a target tracking or aerial combat maneuvering task. The pipper error was set to 1/40 of the pitch attitude command as per Onstott's original definition. This corresponds to a desired performance standard of approximately ±2 mils deviation for a 5 degree step attitude command. This parameter was not varied in the criterion development.

C.3 Acquisition Time: The Time-Domain Task Performance Measure

The most fundamental evolution of the original STT criterion to create the Time Domain Neal-Smith criterion was the re-definition of the acquisition time, D.

In this PIO analysis, the acquisition time, D, was "recast" from Onstott's work to be the required task performance (aggressiveness) imposed upon the "pilot" for the tracking task. The acquisition time parameter would be analogous to the bandwidth parameter of the frequency domain Neal-Smith criterion and thus, would provide the foundation for the PIO criterion by being the task driven performance "forcing function."

The acquisition time, D, was defined as the time at which the pitch attitude error first becomes less than the allowable pipper error after the pitch attitude command step input at 0.25 seconds. The acquisition time definition relates to how rapidly the pilot drives the pipper to the vicinity of the target during the gross acquisition phase.

The correlation of acquisition time to the frequency domain-based Neal-Smith bandwidth was illustrated by a simplistic example in Section 2. The acquisition time, D, is effectively a system bandwidth measure, analogous to the Neal-Smith frequency domain

bandwidth. In this case, however, the task demands imposed upon the closed-loop "pilot" are *increased* as the numerical value of the crossover time *decreases* (compared to an increase in the numerical value of the frequency domain bandwidth).

The bandwidth-acquisition time analogy is illustrated in Figure 8. With this definition of the acquisition time, the system bandwidth is equal to (-1/(D-0.25)*ln(1/40)) for perfect K/s pilot-vehicle open-loop dynamics.

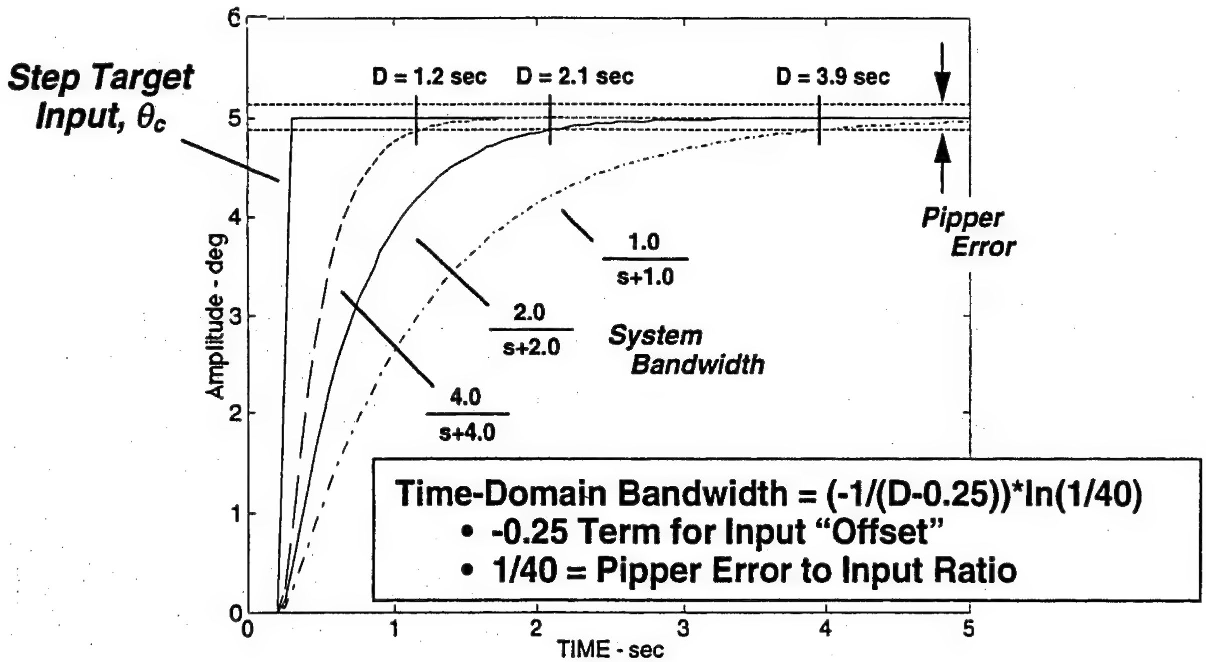


Figure 8: Task Bandwidth and Acquisition Time, D

With the pitch attitude command and allowable pipper error set, the PIO test is established by finding the optimal pilot model compensator which can meet the task demands set by the required acquisition time, D. The acquisition time produces a constrained optimization problem.

C.4 Optimization "Rules"

The pilot compensation and pilot-vehicle loop closure is based upon well-established flying qualities "rules" which form a constrained optimization problem. While it is impossible to fully embellish a mathematical optimization which considers all of the factors that a pilot will

consider in aircraft control and flying qualities evaluation, it is possible to approximate the primary piloting considerations.

The Neal-Smith criterion foundation was used to establish the time domain-equivalent optimization.

The pilot, according to Reference 8, "adapted" to each aircraft configuration to "acquire the target quickly and predictably, with a minimum of overshoot and oscillation." In the frequency-domain, Neal-Smith criterion, these qualities are numerically set by:

1) Requiring a minimum closed-loop bandwidth (i.e., setting a task aggressiveness or performance standard which establishes the speed of closed-loop response)

2) Constraining allowable solutions to a maximum allowable low-frequency "droop" (i.e., driving for steady-state (zero error) tracking performance); and,

3) Minimizing the closed-loop resonance (i.e., maximizing the closed-loop system stability and minimizing the overshoot and oscillation of the closed-loop response).

For the time domain criterion, the acquisition time has been established as the closed-loop task performance or "bandwidth" requirement. For a given value of acquisition time, the "pilot" must achieve a closed-loop pitch attitude response that meets or betters the imposed performance requirement.

To quantify the remaining qualities, many time domain measures are available but the selection is not obvious. Onstott in his original work used rms θ_e and the time-on-target (TOT) as flying qualities performance measures.

A quick analysis was undertaken to check which parameters would best encompass these characteristics for the optimization problem:

- Time-on-target and rms θ_e were shown to be highly correlated and simultaneous usage of these two parameters was counter-productive.

- If rms θ_e or TOT, computed over the entire time history, was used as the optimization parameter, the crossover constraint became irrelevant. This fact was important since the acquisition time parameter, D, was intended to be the required task performance driver. The optimal solution using either rms θ_e or TOT <u>over the entire time history</u> is invariant for many cases with changes in the acquisition time constraint because the optimal solution would occur when the closed-loop system achieves a target acquisition time that is less than the specified acquisition time requirement. Changes in the optimal, constrained solution only occur when the required acquisition time becomes less than the optimal, unconstrained acquisition time solution.

An illustration of the concerns in choosing appropriate performance standards is shown in Figure 9. In this figure, for various system bandwidth performance (i.e., acquisition times, D), two performance measures are shown: 1) rms θ_e computed over the entire time history; and 2) rms θ_e computed <u>after</u> the acquisition time, D.

Using rms θ_e computed over the entire time history as the performance optimization yields an optimal solution unaffected by the crossover parameter constraint, D. For instance, if the closed-loop performance is specified as 3.9 sec (i.e., D=3.90 sec), the pilot compensator will adopt control to approach the 4.0/(s+4.0) system or better to obtain rms $\theta_e \leq 0.75$. The constraint of 3.90 seconds is irrelevant since the 3.90 sec constraint is easily met the 4.0/(s + 4.0) system. A constraint (acquisition time) of 2.10 sec is also irrelevant since the performance for a 4.0/(s + 4.0) system easily meets the constraint. This scenario would be analogous to telling the pilot that he has 4 seconds to achieve a tracking solution and he ignores the instructions and tries to acquire as quickly as he can.

An alternate method is to use rms θ_e <u>after</u> the parameter constraint, D, as the optimization performance index. This situation would be analogous to telling the pilot he has D seconds to achieve a tracking solution with the objective of minimizing the deviation of the pipper from the target after that time (i.e., driving fine tracking to precision). By using rms θ_e after the acquisition time, D, as the optimization index, the optimization bandwidth becomes relatively invariant with changes in closed-loop system bandwidth. The simple illustration in Figure 9 shows that when the required task bandwidth is increased (i.e., acquisition time reduces from 3.9 to 1.2), the optimization performance (rms θ_e after D) remains of constant numerical values but greater levels of pilot-vehicle performance (i.e., more extensive pilot compensation) is required to meet the optimization constraint.

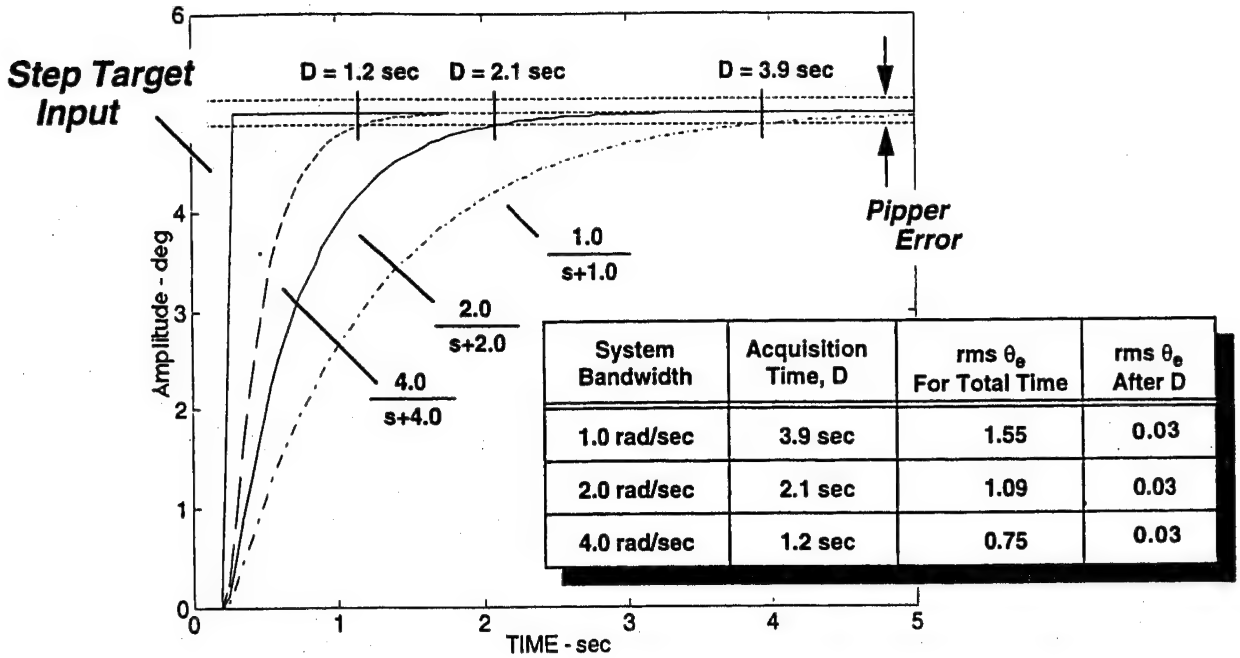
The chosen optimization performance index was the rms θ_e after the acquisition time, D. This parameter directly relates to the precision and stability of the closed-loop response during the "fine" tracking portion of the task (i.e., "minimizing the oscillation of the closed-loop response"). This parameter does not interfere with use of the acquisition time as a constraint (i.e., the aggressiveness/performance standard).

Rms θ_e after the acquisition time, D, and the performance constraint can be related to piloted task instructions:

1) After the step input, the target should be "acquired" and fine tracking should commence by D seconds (i.e., target within the pipper); and,

2) The fine tracking performance objective is to minimize the tracking error (θ_e) deviation after the required acquisition time, D, until the end of the task.

With these performance objectives, it would be reasonable to expect that the analytic pilot - given a long acquisition time, D - would use smooth, non-abrupt inputs to meet the performance objectives and tracking time constraint. Given shorter acquisition time, more aggressive inputs would be required to meet the acquisition time constraint. In either case, the pilot's performance measure is minimizing the deviation of the pipper from the target after the required acquisition time is achieved.



System Bandwidth	Acquisition Time, D	rms θ_e For Total Time	rms θ_e After D
1.0 rad/sec	3.9 sec	1.55	0.03
2.0 rad/sec	2.1 sec	1.09	0.03
4.0 rad/sec	1.2 sec	0.75	0.03

Figure 9: Performance Optimization Measures

A notable omission to the selected performance index is that it does not directly provide a quantitative measure of the initial overshoot in the closed-loop system response nor is it used in the performance optimization. Only the rms θ_e after D is in the optimization objective. The "pilot" in the optimization is allowed to overshoot, without restriction, the attitude target to meet the performance constraint and to minimize the rms θ_e after the acquisition time.

C.5 Pilot Model Structure

Onstott's original work was intuitively pleasing in the modeling of a pilot's behavior in actual target tracking. He had hypothesized that the pilot would initially use a compensation technique to quickly acquire the target. After some time, D, the pilot would change compensation to achieve a tracking solution on the step attitude target, including the use of integral attitude error. This bi-modal pilot model compensator "switched" at the acquisition time, D.

While this bi-modal approach is intuitively pleasing, the bi-modal pilot compensator was dropped from this development. The bi-modal model presented two significant difficulties. The first problem was procedural. The bi-modal model was different than the Neal-Smith model

and analogies to the Neal-Smith criterion would be lost if it were used. Secondly, and more importantly, the bi-modal switch and the forward path integrator in the fine tracking phase could provide unrealistic results by virtue of an optimization which could use these "new" parameters to optimize the closed-loop solution, somewhat arbitrarily independent from the initial acquisition solution parameters.

An example of the bi-modal model is shown to illustrate the deficiency. A PIO-prone configuration was analyzed using the bi-modal pilot model (configuration 6f from Reference 8, with PRs of 8, 8.5, and 10 and PIORs of 4, 4, & 5). In Figure 10, closed-loop time response is shown for two different acquisition time constraints. Intuitively, as the task demands are increased (i.e., acquisition time is decreased), the closed-loop time response should show oscillatory tendencies develop, indicative of PIO. With the bi-modal pilot model, the change in closed-loop time responses is not significant as the task demands are increased. The pilot model parameters in the optimization exhibit unrealistic variations including negative values for the tracking compensator gain on the error signal as the performance demands increased.

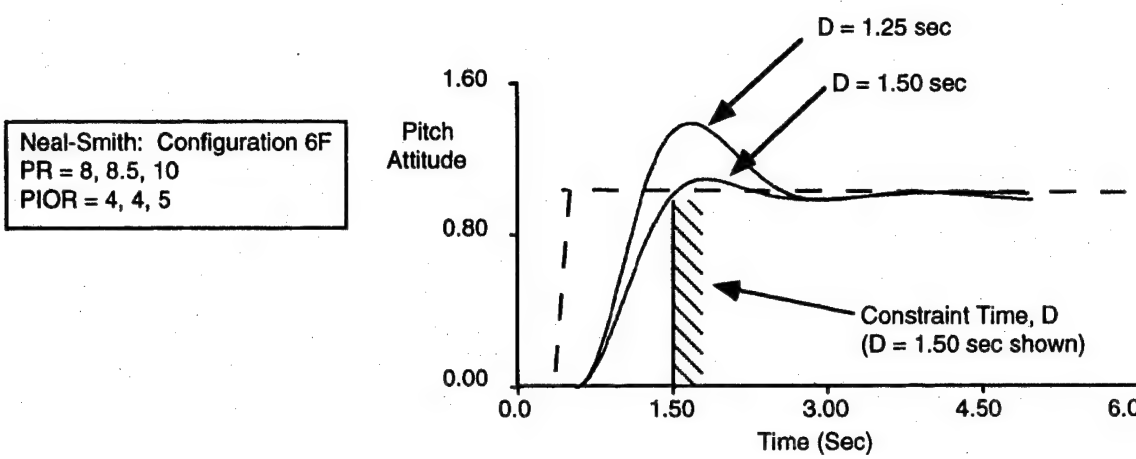


Figure 10: Closed-Loop Performance with Bi-Modal Compensator

Therefore, a single mode pilot model was adopted for this criterion development.

Another significant departure from Onstott's original work is allowing the pilot model to adopt lag compensation (i.e., not only lead) as shown in the following.

The independent parameters in the closed-loop optimization are the pilot gain, K_p, and the pilot compensation time constant, T_L.

In the optimization, positive values of T_L correspond to pilot lead compensation using the model:

$$\delta_{es} = (\text{Delay } \tau)[K_p\theta_e(t) + T_L(d\theta_e(t)/dt)]$$

(The pilot compensator control output is shown as δ_{es}. This term is assumed to be either a force input for force command control systems or a position command for position command control systems. The importance of controller or feel system dynamics on the pilot compensator is recognized (e.g., Reference 20 and 21) but it has not been incorporated into the criterion nor into the pilot compensator model. The position taken in this criterion development is that the feel system is critically important to flying qualities but its effects are not evaluated using this criterion; other criteria are necessary to assess this influence (e.g., Reference 20))

Negative values of T_L correspond to pilot lag compensation, using a lead-lag compensator (written in Laplace notation, excluding the delay term for illustration):

$$(\delta_{es}/\theta_e) = K_p(t_{p_1}s + 1)/(t_{p_2}s + 1)$$

For lead-lag compensation, the equalization rules from the Neal-Smith criterion are adopted to determine the optimal compensation.

To compute this compensation in the time domain, a equivalent bandwidth frequency is computed. The bandwidth frequency is defined from the acquisition time performance requirement with the "perfect" compensator assumption:

$$\omega_{BW} = (-1/(D-0.25))*\ln(1/40).$$

where

D is the required acquisition time (sec);

(1/40) is the pipper error to target command ratio.

The lag term, t_{p_2}, is computed as:

$$t_{p_2} = \left(\frac{1}{\omega_{BW}} - T_L\right)$$

The lead term, t_{p_1}, is computed as:

$$t_{p_1} = 1/(t_{p_2}\omega_{BW}^2)$$

The chosen pilot model is completely analogous to the Neal-Smith criterion. The pilot model compensator is written in a time domain representation, including a delay, term τ which accounts for the neuromuscular and reaction time delay of the human operator.

A total delay of 300 msec was felt to be representative for the pilot compensator in this criterion. Variations in this value were not investigated.

The total 300 msec of pilot delay was actually represented by a pure delay ($e^{-\tau s}$) of 230 msec and a 2nd order lag filter with a break-frequency of 20 rad/sec (damping ratio of 0.7). These two elements created a total equivalent time delay of 300 msec for the pilot model compensator. This system is sketched in Figure 11.

The reason for using a 2nd order lag filter to provide 70 msec of equivalent delay was purely for aesthetics. The lag filter produced time histories which were more pleasing to the analyst and more representative of actual tracking task time history data. Unrealistic control input rate time responses are generated by the algorithm model without the 2nd order lag dynamics.

A quick analysis was made on the effect of this lag filter as opposed to a simple 300 msec pure delay. There were no significant differences in the criterion results. Hence, this equivalent approximation was considered appropriate.

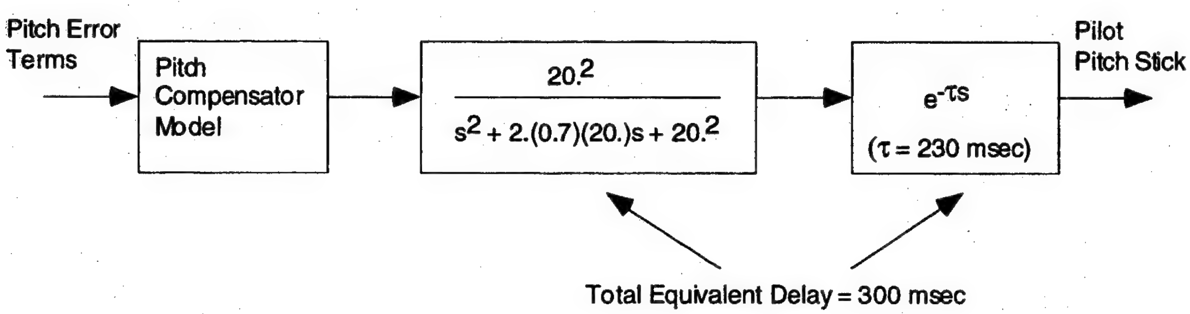


Figure 11: Time Delay Modeling for the Pilot Compensator

C.6 Optimization Procedures

The optimization algorithm is outlined in Appendix C. In summary, the process is:

1) Given an augmented aircraft configuration time domain representation with a defined pilot pitch control input (δ_{es} or F_{es}) and pitch attitude response output (θ); and,

2) Using a pitch attitude step command of TBD degrees at 0.25 seconds and a TBD pipper error limit (5 degrees and 0.125 degrees, respectively, were used exclusively in this development for the TBD values);

3) Optimization is performed over the 5 seconds of time history with a required acquisition time, D, serving as an optimization constraint. The pilot compensator parameters of gain (K_p) and compensation value (T_L) are adjusted to minimize, under the acquisition time constraint, the rms θ_e after the acquisition time.

4) The output parameters are the closed-loop tracking performance time history measurements (particularly, the rms θ_e after D) and the optimal pilot compensator values of gain (K_p) and compensation (T_L).

C.7 Acquisition Time Constraint and the Required Task Performance

Variation of the acquisition time, D, corresponds to changes in the "aggressiveness" of task performance (i.e., task demands) and the speed of the closed-loop response. These changes should produce intuitive variations in the closed-loop time history responses and the optimal pilot compensator.

A good configuration - one with good flying qualities and without PIO tendencies - should *not* show significant variation in closed-loop response character as the task demands increase. For a good, PIO-immune aircraft configuration (configuration 7c from Reference 8: PRs of 3, 3,4, and 1.5; PIORs of 2, 2, 1, and 1), the variation of closed-loop time responses is shown in Figure 12. As the task demands are increased, the closed-loop time responses do not shown significant change. Oscillatory tendencies, indicative of PIO, are not apparent in the closed-loop time responses.

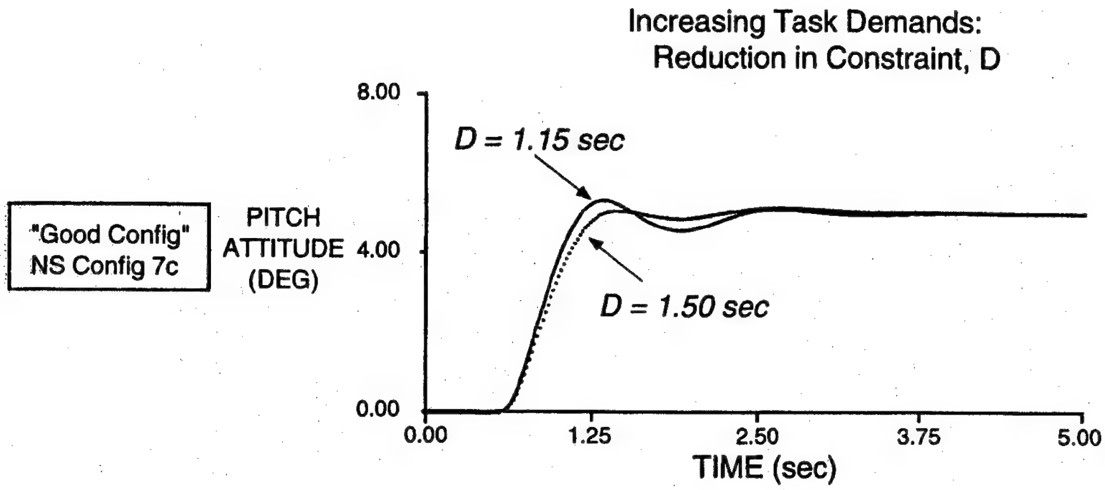


Figure 12: Variation in Required Task Performance - PIO-Immune Configuration

A poor configuration - one with bad flying qualities and PIO tendencies - should show significant variation in closed-loop response character as the task demands increase. Good task performance can sometimes be obtained for poor configurations if the pilot can adopt more open-loop control characteristics and if sufficient time is available in the task so that abrupt or tight control inputs are not necessary. However, as the task demands increase or pilot lead compensation is used, the PIO tendencies become evident and oscillatory closed-loop behavior occurs. For a bad PIO-prone aircraft configuration (Configuration 5c from Reference 8, PRs of 9 and 7; PIORs of 5 and 4), the variation of closed-loop time response as the task demands are increased show these intuitive results (Figure 13). As the task demands are increased, the closed-loop time responses show unstable oscillatory change. Such oscillatory tendencies are indicative of PIO and the divergent oscillations correlate to closed-loop instability.

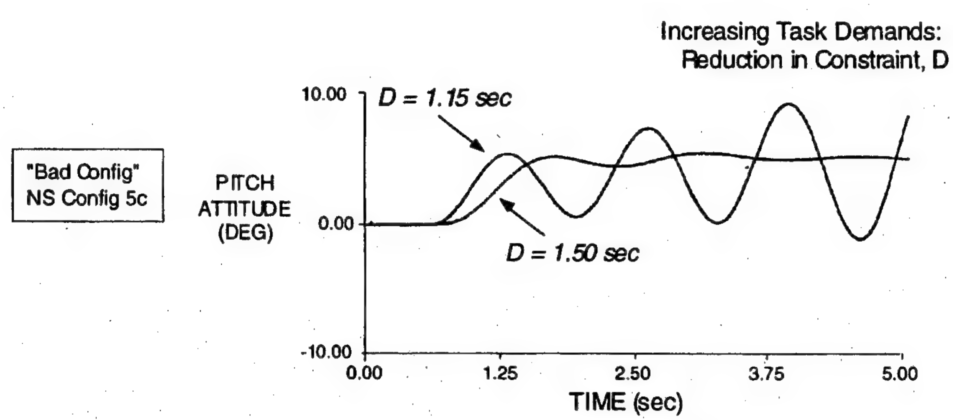


Figure 13: Variation in Required Task Performance - PIO-Prone Configuration

C.8 Flying Qualities Definition

Flying qualities are defined by the closed-loop performance and attendant pilot workload. Quantitative measures of workload and performance are drawn from the closed-loop model and optimization procedures to provide quantitative flying qualities measures. Once again, the Neal-Smith criterion is used as the basis for the time domain analysis.

The Neal-Smith parameter plane (Figure 3) consists of the phase angle of the pilot compensator measured at the bandwidth frequency and the closed-loop resonance. The phase angle of the pilot compensation is directly related to the compensation required by the pilot model to achieve the task performance. Pilot compensation or control technique is one measure of pilot workload. Closed-loop resonance is a measure of closed-loop stability which, consequently, is a measure of closed-loop oscillatory behavior and PIO.

For the time domain Neal-Smith equivalent, a pilot compensation measure was computed from the pilot compensator model. The "perfect" compensator assumption was again used to approximate a bandwidth frequency:

$$\omega_{BW} = (-1/(D-0.25))*\ln(1/40).$$

The phase angle of the compensator was computed using this "bandwidth" frequency, ω_{BW}, and the pilot compensation.

For a lead compensator, pilot compensation phase angle, $\angle_{pc}$, equals:

$$\angle_{pc} = 57.3\tan^{-1}(T_L\omega_{BW})$$

For the lead-lag compensator, pilot compensation phase angle, $\angle_{pc}$, equals:

$$\angle_{pc} = 57.3\tan^{-1}(t_{p_1}\omega_{BW}) - 57.3\tan^{-1}(t_{p_2}\omega_{BW})$$

The time domain equivalent for the closed-loop resonance was "chosen" to be the rms θ_e after the acquisition time. Two primary reasons prompted this decision: 1) the parameter is directly a measure of the closed-loop stability; and, 2) the parameter is minimized in the optimization. Both of these factors are equivalent to the frequency domain resonance parameter formulation.

C.9 Flying Qualities Criterion Development

By carrying the analogies between the time domain and frequency domain criterion output parameters, a time domain Neal-Smith parameter plane was envisioned, as shown conceptually in Figure 14.

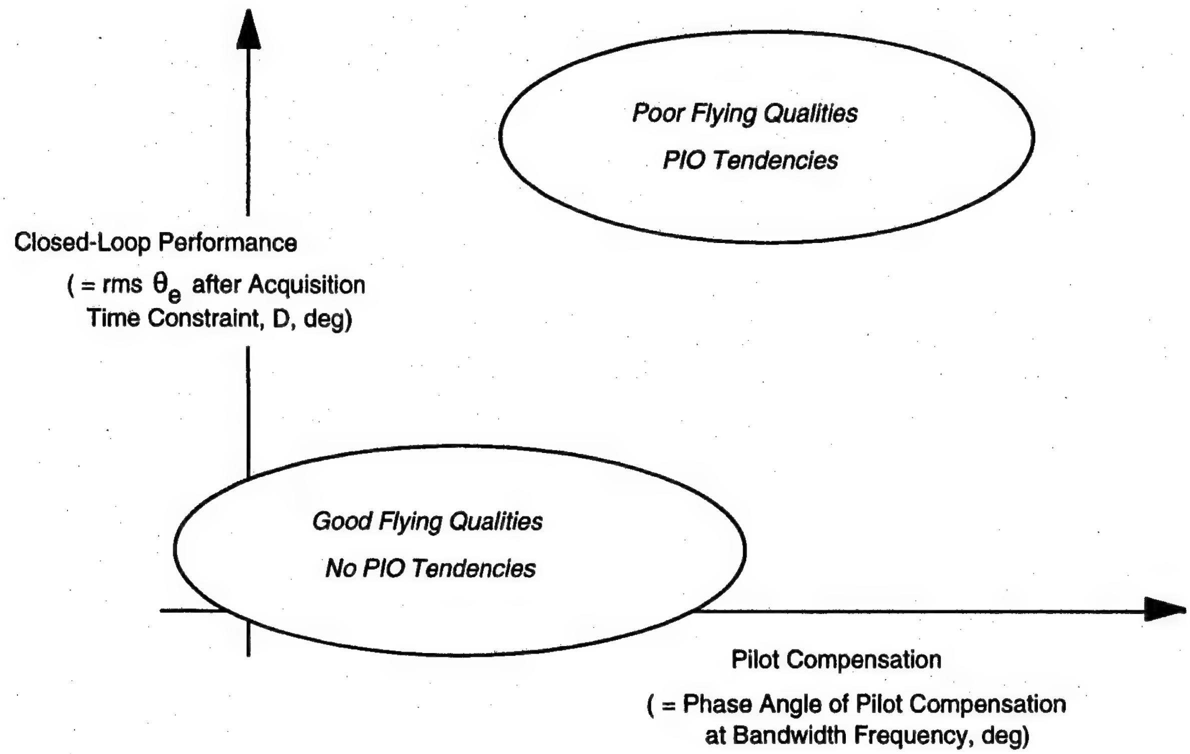


Figure 14: Time Domain Neal-Smith Parameter Plane

Three data bases were used for validation of the Time Domain Neal-Smith criterion against this conceptual parameter plane. The intent was to investigate the equivalence between the frequency domain and time domain analyzes and to validate that the time-domain-criterion flying qualities "outputs" (i.e., rms θ_e after acquisition and phase at the equivalent bandwidth) are, indeed, sensitive measures of flying qualities. This was not intended to be the primary purpose of this investigation but was meant to serve as a sanity check. If the flying qualities results are comparable to the frequency domain Neal-Smith criterion, then the likelihood of success in fashioning a PIO criterion (the primary objective of this work) was favorable.

1.) Neal-Smith Data Base (Reference 8)

The Neal-Smith data base can be separated into two sets for analysis: 1) Configuration set 1 through 5 were conducted at 250 KIAS; and, 2) Configuration set 6 through 8 were conducted at 350 KIAS. Analysis of the Neal-Smith data in Reference 8 showed that the 250 KIAS configurations were flown less aggressively than the 350 KIAS configurations because of the buffet boundary limitation of the NT-33 in-flight simulator at 250 KIAS. For the frequency domain, Neal-Smith analysis, the 250 KIAS configurations were analyzed using a bandwidth frequency of 3.0 rad/sec and the 350 KIAS configurations were analyzed using a bandwidth frequency of 3.5 rad/sec.

The correlation of the Neal-Smith 250 KIAS configurations with the frequency domain Neal-Smith criterion is shown in Figure 15. The criterion parameters were extracted from the original work of Reference 8. Median pilot ratings are plotted for each configuration (using Level 1, Level 2, and Level 3 distinctions) to indicate the correlation with the criterion. All of the pilot rating and PIO rating data are shown in Appendix E with the median ratings that are used in these figures. (Of course, the proper correlation of the flying qualities data to any criterion includes the individual, rather than median ratings, as well as the associated pilot comments. Therefore, these correlations are shown to illustrate trends without the benefit of the pilot comment data; during criterion development, more detailed understanding and interpretation of the data was made than just the simple use of median ratings would indicate.)

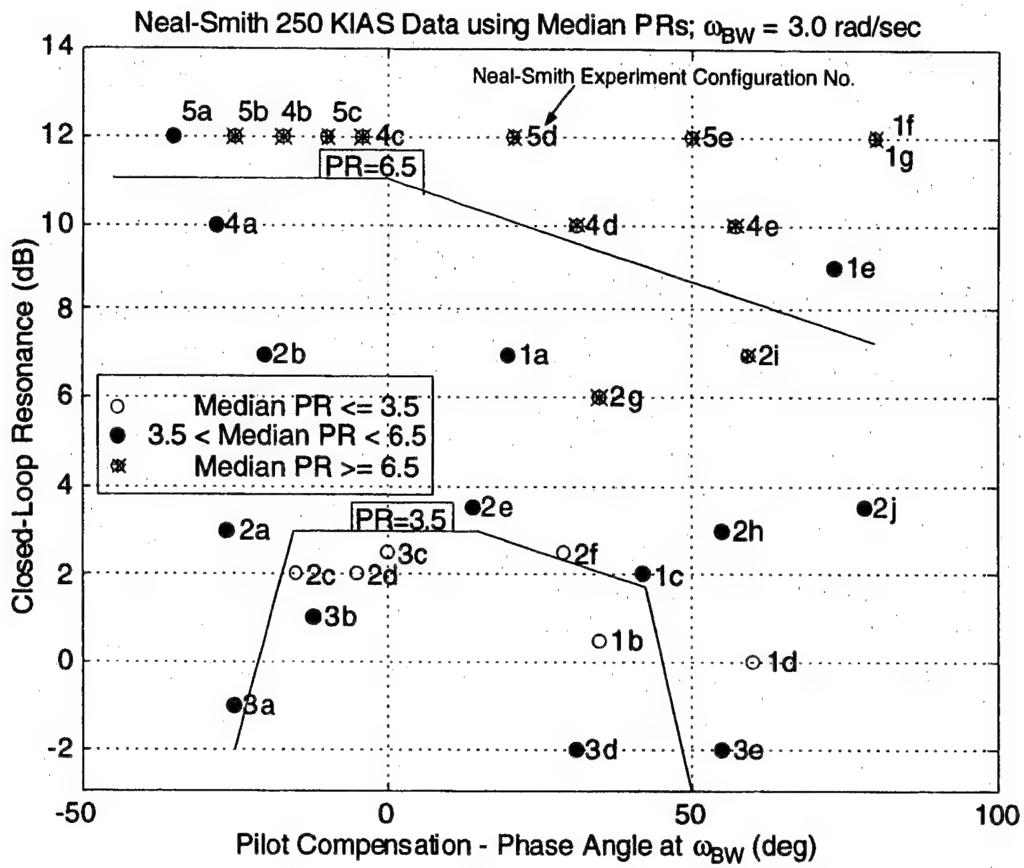


Figure 15: Frequency Domain Neal-Smith Criterion: 250 KIAS Neal-Smith Data; Required Task Bandwidth, ω_{BW} = 3.0 rad/sec

The correlation of the 350 KIAS Neal-Smith configurations against the frequency-domain Neal-Smith criterion is shown in Figure 16.

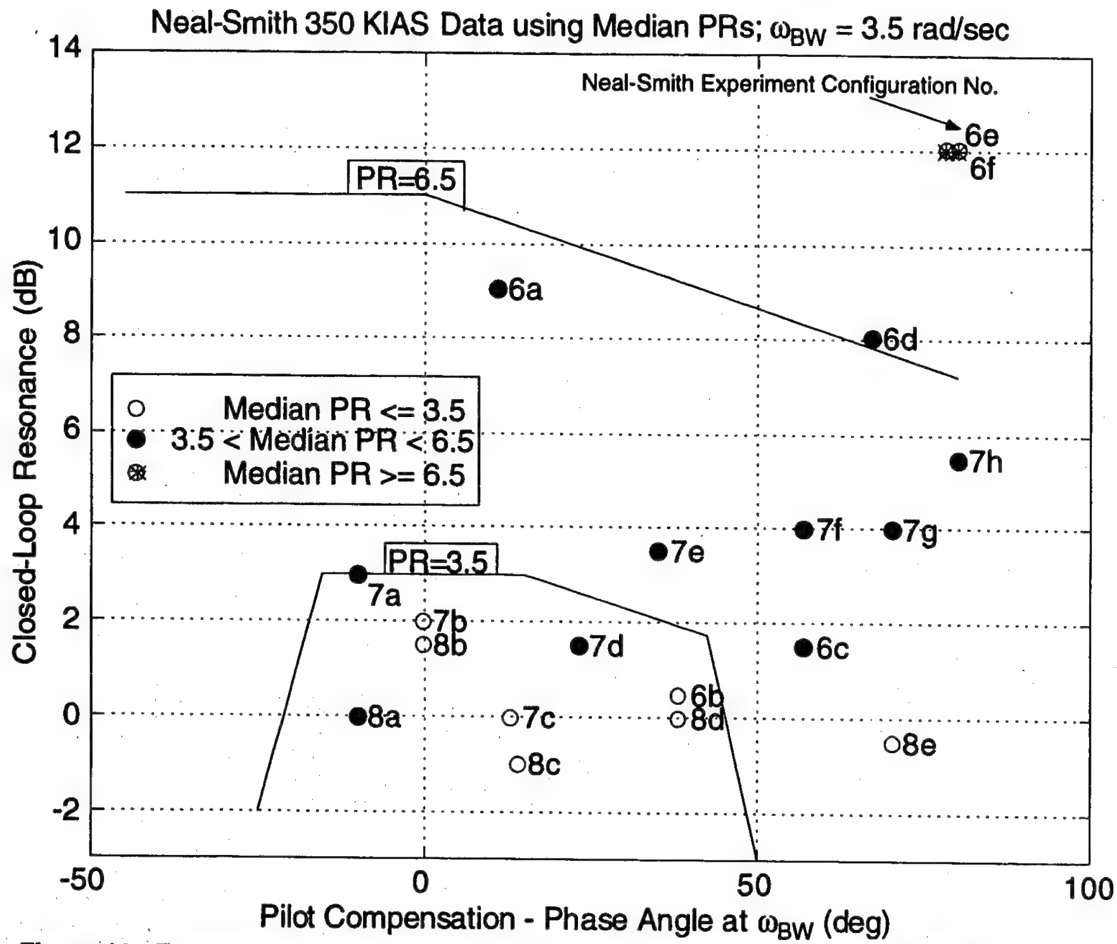


Figure 16: Frequency Domain Neal-Smith Criterion: 350 KIAS Neal-Smith Data; Required Task Bandwidth, ω_{BW} = 3.5 rad/sec

Both Figures 15 and 16 show good discrimination of the configurations into their expected flying qualities level groupings.

The analysis of these same configurations using the new Time Domain Neal-Smith criterion produced very similar results. The analysis results of the 250 KIAS Reference 8 configurations is shown in Figure 17 and the analysis results of the 350 KIAS configurations is shown in Figure 18.

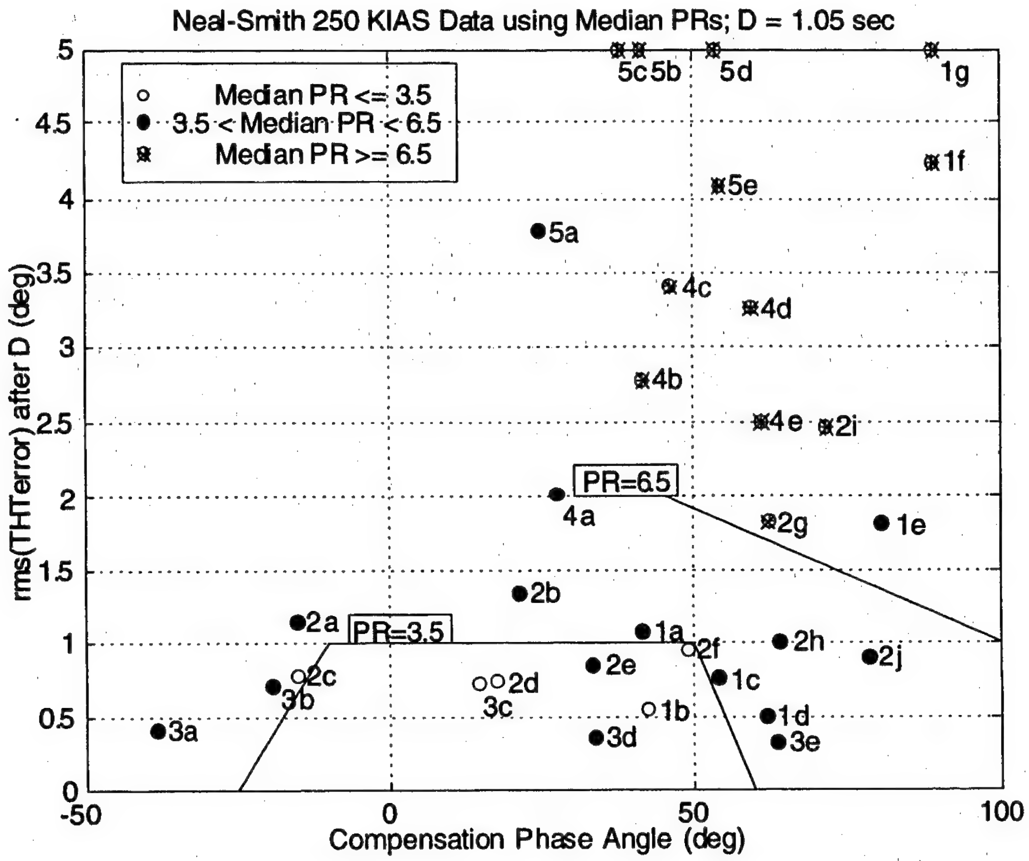


Figure 17: Time Domain Neal-Smith Criterion: 250 KIAS Neal-Smith Data; Required Acquisition Time, D = 1.05 sec

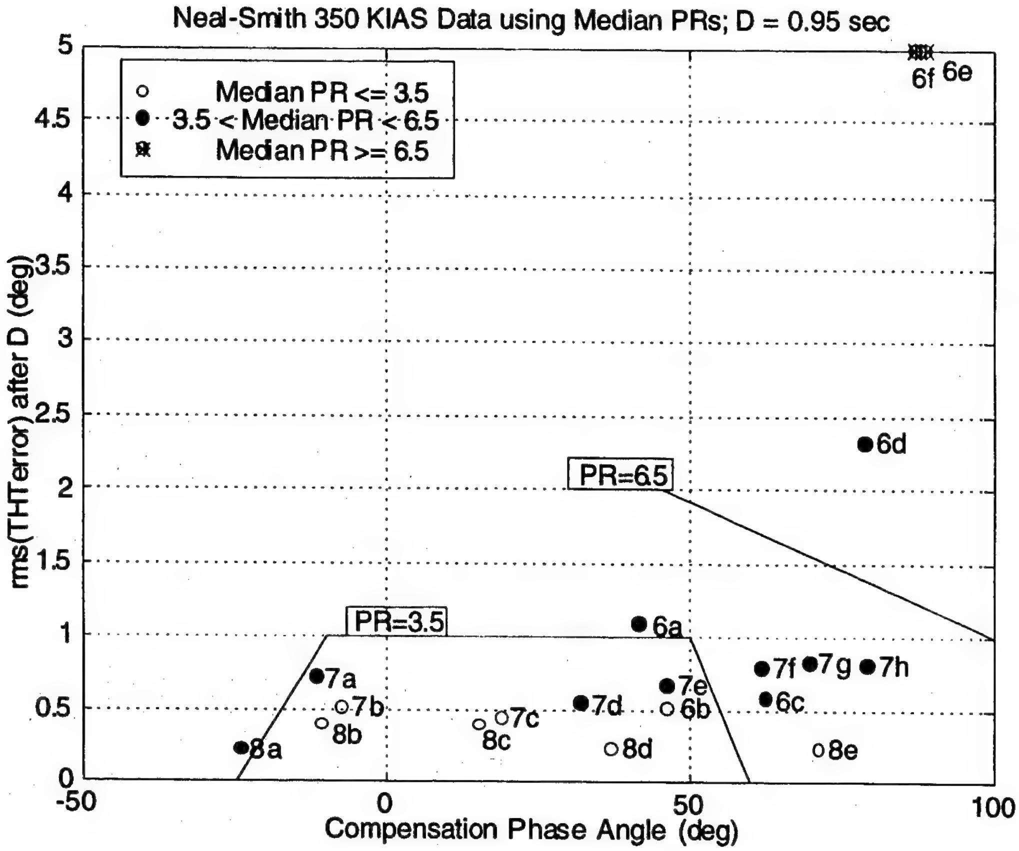


Figure 18: Time Domain Neal-Smith Criterion: 250 KIAS Neal-Smith Data; Required Acquisition Time, D = 0.95 sec

For the Time Domain Neal-Smith criterion, the phase angle of the pilot compensation is plotted against the rms θ_e after D. Level boundaries denoting lines of "constant" flying qualities equal to pilot ratings of 3.5 (Level 1/Level 2 boundary) and 6.5 (Level 2/Level 3) boundary are drawn. Good Level 1 flying qualities correspond to configurations that do not require significant pilot compensation (i.e., low workload corresponding to little or no phase angle compensation) and do not exhibit significant overshoot and oscillation (i.e., low rms θ_e after D).

The required task "aggressiveness" for the 250 KIAS configurations was reduced from that used for the 350 KIAS configurations as was done for the Frequency Domain Neal-Smith criterion application. For the 250 KIAS configurations, the required acquisition time was 1.05 seconds. For the 350 KIAS configurations, the required acquisition time was 0.95 seconds.

The correlation between the median pilot ratings and the Time Domain Neal-Smith criterion is very good. The Level 1 configurations are generally grouped into the Level 1 region of the criterion and the Level 3 configurations are generally grouped into the Level 3 region of the criterion. Some discrepancies are shown but the general trends are evident.

Comparison between Figure 15 and Figure 17 and Figure 16 and Figure 18 show both the similarities and differences between the Frequency Domain and Time Domain Neal-Smith criteria:

- With only a few exceptions, the placement of a configuration in the Frequency Domain criterion is mapped one-to-one to the Time Domain criterion parameter plane.

- Some interpretation is required for this mapping however, because the y-axes in the Frequency Domain and Time Domain are somewhat different due to parameter definition and units (i.e., the differences between the frequency domain, closed-loop resonance parameter, $|\theta/\theta_c|_{max}$ and the time domain, rms θ_e after D parameter).

- The relationship between configuration "families" is generally preserved between the frequency domain and the time domain criteria. For instance, following a family such as Configurations 6a through 6f in the Frequency or Time Domain criteria shows the same general relationship of increasing required lead compensation and increasing resonance $|\theta/\theta_c|_{max}$ or increasing rms θ_e.

- The exceptions to the one-to-one domain mappings are the "lightly damped" configurations (Configuration family 4 and 5) in Figures 15 and 17. In the Frequency Domain analysis, lag pilot model compensation is employed for optimal performance for the lightly damped configurations with minimal control system lags (e.g., Configurations 4a - 4c and Configurations 5a - 5c). In the Time Domain analysis, all lightly damped configurations use lead compensation. In both domains, however, Level 3 flying qualities are predicted for these configurations because of poor closed-loop stability (high resonance or high rms θ_e values).

- Comparison of time histories from the time domain model and the frequency domain pilot model show good correlation.

These results show that a Time Domain equivalent of the Frequency Domain Neal-Smith criterion has been established for the Reference 8 data base.

2.) LAHOS Data Base (Reference 17)

The LAHOS data base, generated for a fighter type approach and landing task, was analyzed using the Time Domain Neal-Smith criterion. In this case, a required acquisition time D of 1.15 sec provided the best correlation between the Reference 17 flying qualities data and the criterion flying qualities levels boundaries. This required task bandwidth (aggressiveness) is less than that used for either the 250 KIAS or 350 KIAS Reference 8 configurations. This relaxation of bandwidth appears to be reasonable considering that the landing approach task is somewhat, but not considerably less demanding than up-and-away fighter aerial combat maneuvering tasks.

The analysis of the LAHOS data (median PRs) using the Time Domain Neal-Smith criterion is shown in Figure 19.

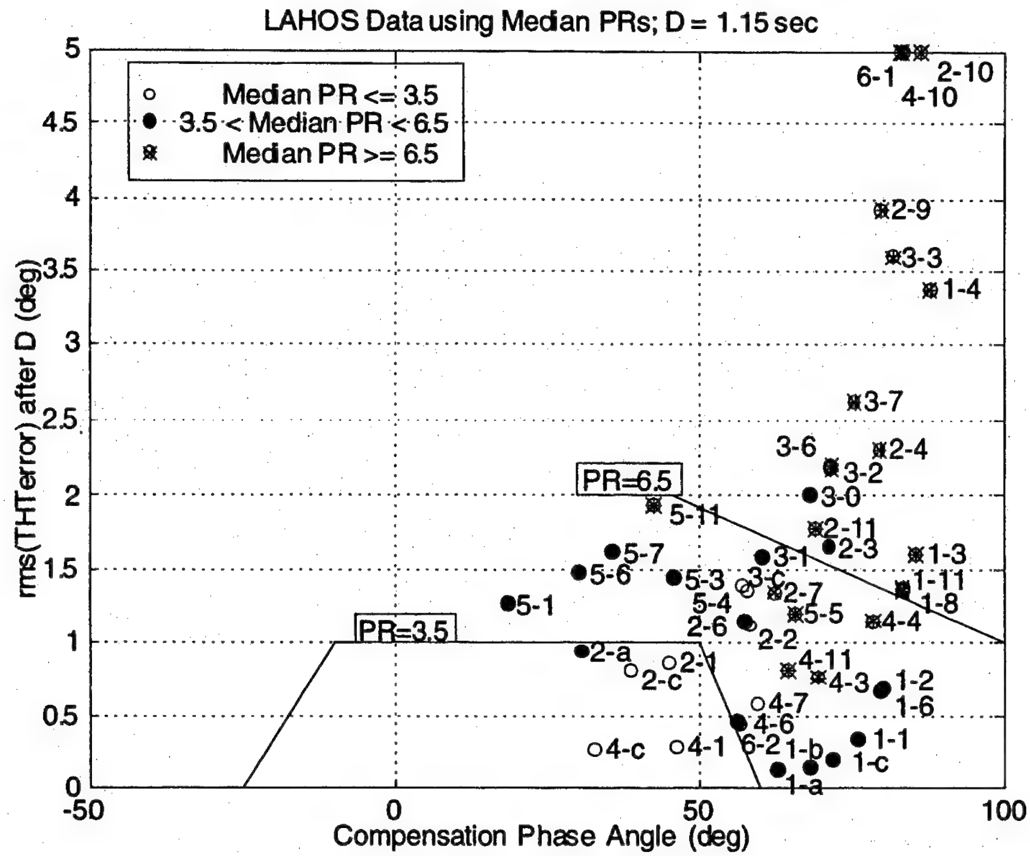


Figure 19: Time Domain Neal-Smith Criterion: LAHOS Data; Required Acquisition Time, D = 1.15 sec

The correlation of the LAHOS configurations with the time domain Neal-Smith criterion shows very good discrimination of the Level 1 and Level 3 flying qualities configurations. Some discrepancies between the predicted Level 2 and actual flying qualities of several configurations is apparent but this disparity for the Level 2 correlations has been an issue with the data base previously (e.g., Reference 5) and is not considered to be a criterion deficiency.

3.) TIFS Pitch Rate Data Base (Reference 18)

The TIFS Pitch Rate program data base was analyzed using the Time Domain Neal-Smith criterion. This data was generated using the USAF TIFS aircraft for a generic transport (Class III) aircraft. The experimental data is comprised of various control law augmentation concepts. Flying qualities deficiencies, if they are apparent, were not caused by (equivalent) time delay problems, such as those for the previous two data bases, but were produced by either:

deficient pitch attitude dynamics; deficient flight path dynamics; disassociation or disharmony of the pitch and flight path responses to pilot control input; or any combination of the preceding.

The Time Domain Neal-Smith criterion, in its current state, invokes the assumption, just as the Frequency Domain Neal-Smith criterion does, that satisfactory pitch attitude (inner loop) response characteristics are a necessary but perhaps not sufficient prerequisite to good longitudinal flying qualities. The criterion which utilizes a pitch attitude loop closure will be a test of pitch control only. Deficiencies in flight path or disharmony between the aircraft pitch attitude that maybe factors in an aircraft's longitudinal flying qualities will not be accounted for without extensions to this criterion.

The correlation of the Time Domain Neal-Smith criterion with the TIFS pitch rate data base is presented in Figure 20. A required acquisition time D of 1.50 sec was used. This "bandwidth" is less demanding than the LAHOS task bandwidth. This difference is intuitive considering the lower task bandwidth requirement for a transport aircraft flared landing than for a fighter aircraft flared landing.

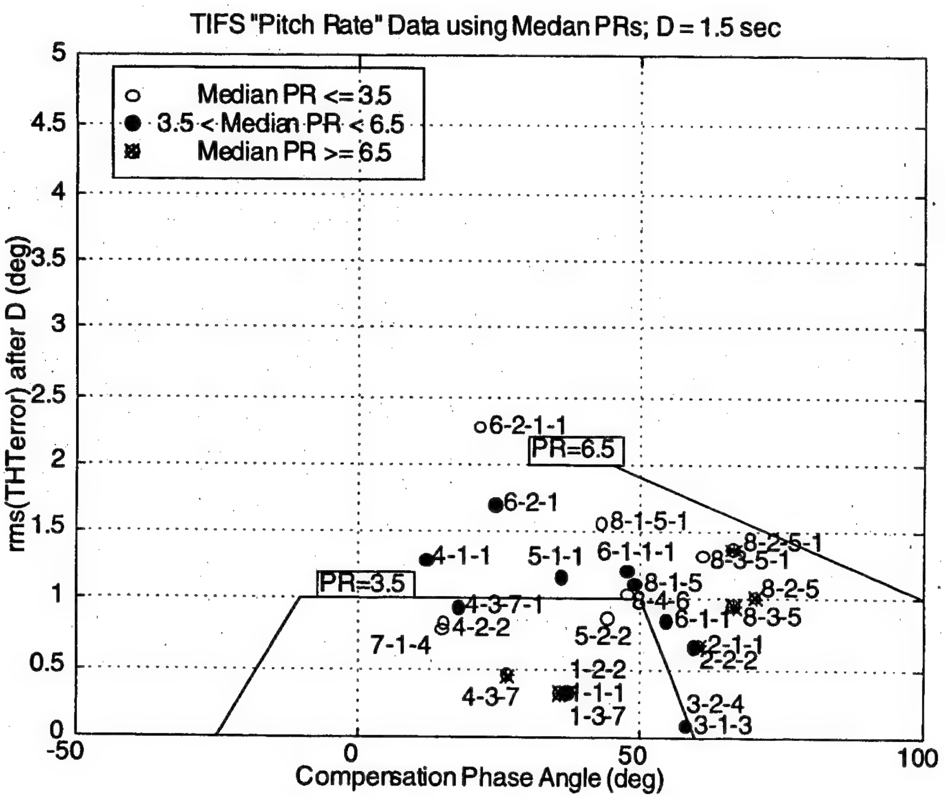


Figure 20: Time Domain Neal-Smith Criterion: LAHOS Data; Acquisition Time, D = 1.50 sec

As expected, the correlation between the Time Domain Neal-Smith criterion and the TIFS pitch rate program data base was not favorable. The pitch-only criterion, in its current state, is not sufficient to analyze this data base.

In general, Level 1 configurations are grouped in the Level 1 area with the exception of the "wash-out" configurations. This result validates the assumption that the criterion is necessary but perhaps not sufficient.

For instance, configurations 1-1-1, 1-2-2, and 1-3-7 overlay each other in the Time Domain Neal-Smith parameter plane because each configuration has an identical pitch attitude response to pilot stick inputs. The pitch dynamic response characteristics are considered to be acceptable. However, the configurations varied significantly in terms of their flight path response to pitch stick inputs and their attendant flying qualities varied from Level 1 (PR=3) to Level 3 (PR=8). Clearly, these significant flying qualities differences, caused by "outer-loop" dynamic response characteristics, cannot be discriminated by the "inner-loop" pitch-only criterion.

Work was started at generating "extensions" to the Time Domain pitch-only criterion to resolve this problem. This work progressed to the point that several avenues showed promise whereby the necessary but perhaps not sufficient assumption of the criterion could be removed.

Unfortunately, other data bases must be used, in addition to Reference 18, in order to produce a viable criterion. The Reference 18 data alone is not sufficient for this criterion to be useful. Resource limitations did not permit bringing in these other works. Also, this work would not be channeled toward the primary emphasis of this work - that is, the development of a quantitative PIO criterion.

For the time being, this criterion work will be restricted to the analysis of pitch control only and the "necessary but perhaps not sufficient" caveat will be retained. Failure of this proposed PIO test will predict that deficient pitch flying qualities are present. Passing this test will not, however, guarantee that flight path or other "outer-loop" longitudinal flying qualities deficiencies will not be resident since this test will not accurately screen these characteristics at this time.

4) Flying Qualities Summarization

The Time Domain Neal-Smith criterion has been shown to be analogous to the Frequency Domain Neal-Smith criterion; thus, the criterion output parameters of compensation phase angle and rms θ_e after the acquisition time, D, appear to be sensitive to pitch flying qualities. Also, the acquisition time, D, has been shown to be analogous to the required task bandwidth (ω_{BW}).

C.10 PIO Analysis Procedures

As noted in Section 2, the key facet in the development of a PIO criterion using the Neal-Smith criterion is the relationship between the task bandwidth and the flying qualities output parameters. The task bandwidth serves as the "forcing function" or input to the PIO test. The hypothesis is that the existence of PIO is directly correlated to a configuration that is very sensitive to task bandwidth changes. With the closed-loop criterion model, the task bandwidth variations correspond to the pilot being more aggressive in flying the aircraft, the task demands changing, and/or the pilot adopting different control strategy or behavior. All of these factors have been cited as causes or coincidental factors in real PIO experiences. Thus, the model offers a mathematical relationship to the physical phenomena.

To explore the relationship between the required task bandwidth (for the case of the Time Domain Neal-Smith - the acquisition time, D) and the criterion output parameters, mappings were created for all of the configurations from References 8 and 17. In Figure 21, an example of the configuration mapping is given, using Config 3c from Reference 8.

(As stated in the previous section, the data from Reference 18 was also analyzed, but, due to the aforementioned assumptions, those results will not be covered since they confuse the issues. Essentially all of the Reference 18 configurations "pass" the PIO test. However, some of the configurations are, in fact, PIO-prone because of deficiencies in flight path or "outer-loop" longitudinal control. No restrictions on the present criterion are shown by using these data, but extensions are required to the current methodology for accurate interpretation of the "outer-loop" flying qualities/PIO results. Preliminary work has been performed but it is not fully validated. Therefore, these results are not covered at this time.)

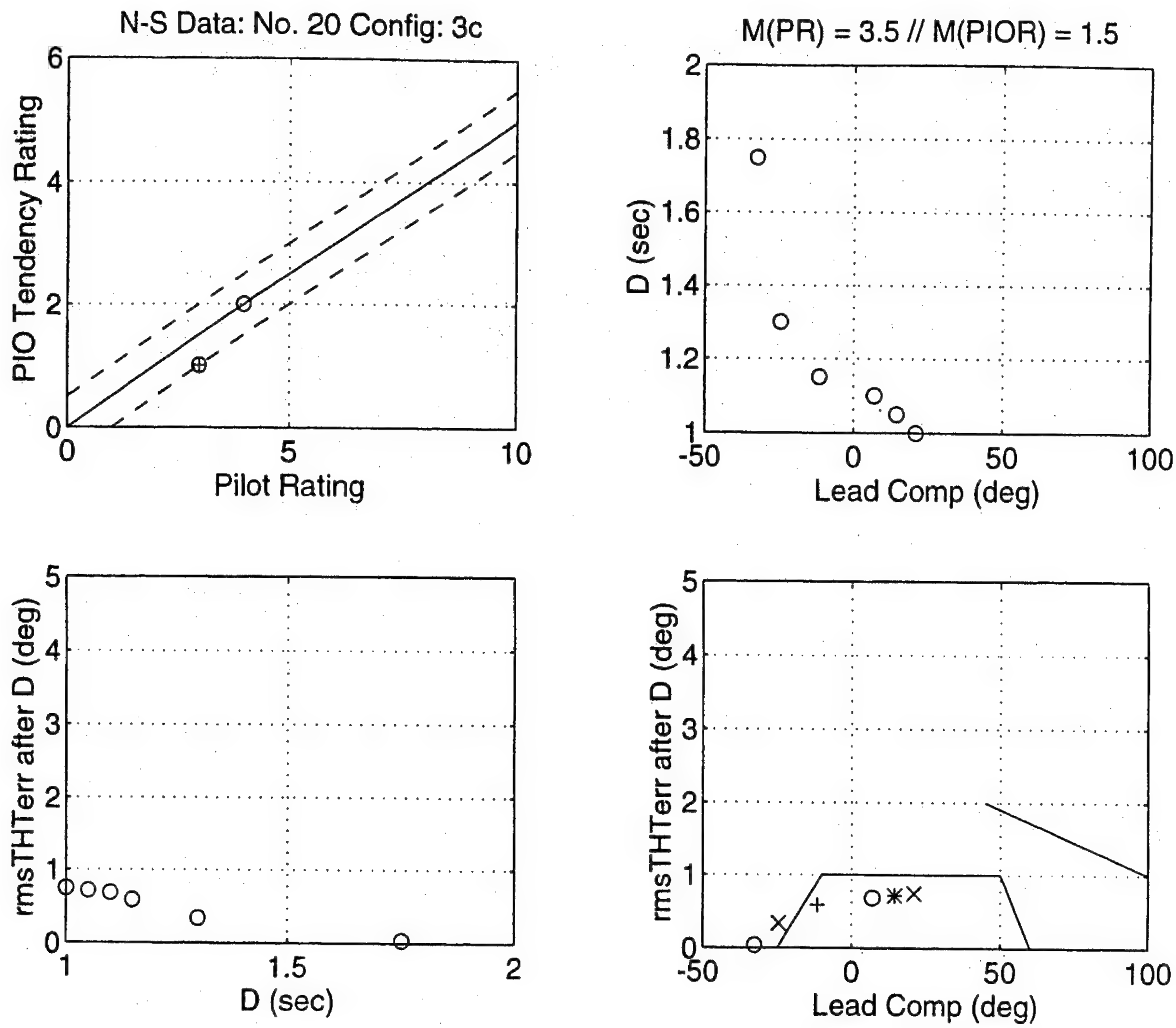


Figure 21: Configuration Mapping - Configuration 3c from Ref. 8

The configuration maps (e.g., Figure 21) consist of four subplots. The upper left hand subplot is a cross-plot of the PRs and corresponding PIORs that were given for this configuration. The data contained in Appendix E was used. (The median PR, M(PR), and median PIOR, M(PIOR), for the configuration is labeled above the upper right hand plot. This data was used in Figures 15-20) The other three subplots show the configuration mapping which consists of the results for computing the closed-loop criterion for various values of D. In the lower left hand subplot, the rms θ_e (after D) data are shown for the configuration as D was changed. The upper right hand plot shows the required phase angle compensation (labeled "Lead Comp (deg)") for each value of D. Finally, these two parameters are collapsed and shown on the Time Domain Neal-Smith parameter plane with the various values of D designated by different plot symbols.

The lower right hand subplot is analogous to the Frequency Domain Neal-Smith configuration map shown in Figure 4. This plot illustrates how a configuration "moves" on the criterion parameter plane as a function of the required task performance (or pilot aggressiveness used in the task).

The hypothesis was that the PIO criterion development would be based on this movement. PIO-prone configurations (at least in the Frequency Domain Neal-Smith criterion) move very rapidly through the parameter plane for relatively small increases in task bandwidth (ω_{BW}). This case is illustrated in Figure 4.

(Configuration maps for selected Reference 8, 17, and 18 configurations are given in Appendix D. These maps were instrumental in the development of the PIO criterion which follows.)

Another example of the configuration maps is given in Figure 22. This configuration is PIO-prone as evident from the PIORs of 4 given on two evaluations. In particular, note the significant increase in rms θ_e (after D) which occurs as the task demands increase (decreasing D). The closed-loop stability of the system deteriorates rapidly for relatively minor changes in the value of D.

The LAHOS configurations show similar, if not identical trends. In Figure 23, a very good configuration, LAHOS Configuration 2-1, is plotted on a criterion map. As D is decreased, an almost imperceptible change in rms θ_e is shown. The closed-loop stability of this configuration is insensitive to task demands which would be consistent with the pilot rating and PIO rating data given for this configuration.

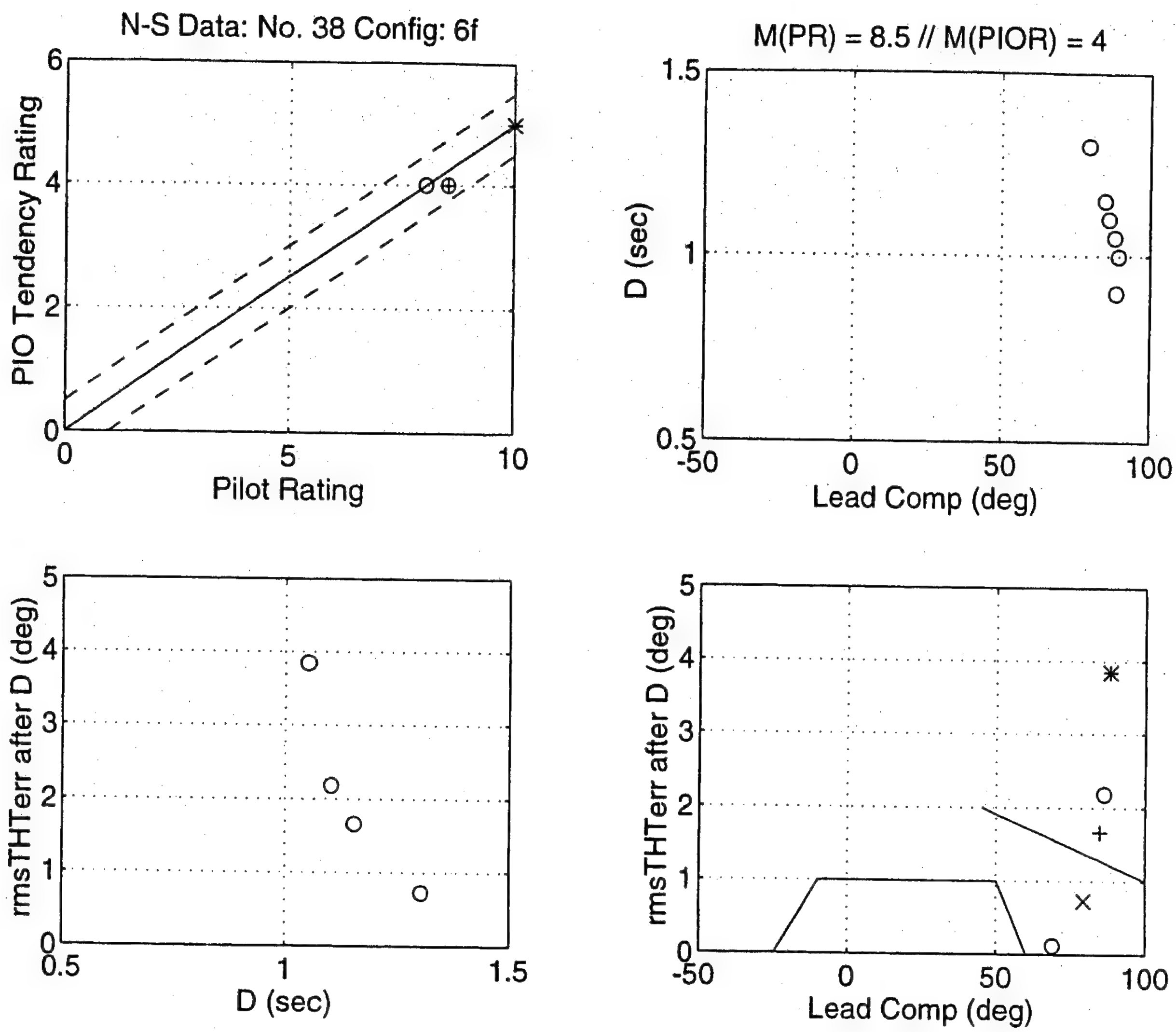


Figure 22: Configuration Mapping - Configuration 6f from Ref. 8

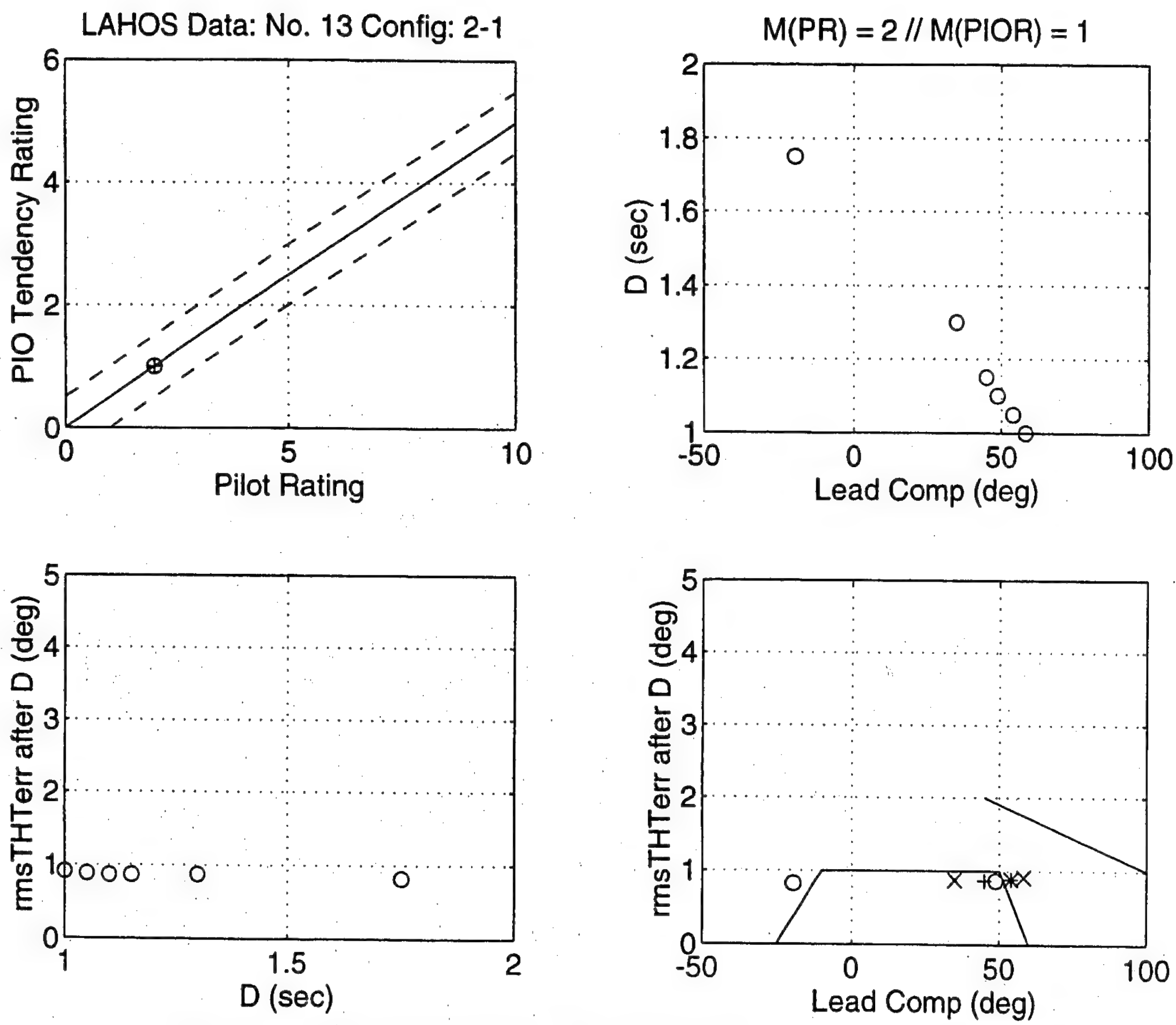


Figure 23: Configuration Mapping - Configuration 2-1 from Ref. 17

In Figure 24, a PIO-prone LAHOS configuration, Configuration 5-11, shows a dramatically different trend than configuration 2-1. As D is reduced from 1.75 sec toward 1.00 sec, the rms θ_e quickly increases; hence, closed-loop stability quickly deteriorates as the task demands are increased. The PIO tendencies of this configuration are accurately depicted by this change in rms θ_e with respect to D.

These trends are consistent throughout the Reference 8 and Reference 17 data base (shown in Appendix D). PIO-prone configurations show dramatic increases in rms θ_e (after D) as the value of D is reduced. PIO-immune configurations do not show significant changes in rms θ_e as D is decreased.

The physical relationship that this criterion relationship shows is that for PIO prone configurations, the closed-loop stability or oscillatory tendencies in the pitch attitude pilot-vehicle system rapidly deteriorates as the required task demands or pilot aggressiveness increases.

C.11 Rate Limiting Example

A primary emphasis of this PIO criterion development is on the time domain aspects of the criterion and its ability to handle nonlinear analysis without compromise. The analysis of actuator rate limiting and its potential to cause PIO is demonstrated by the criterion mapping techniques.

Three hypothetical configurations were developed from one existing configuration. (The hypothetical configurations were used because of the lack of data available at the time. Data now exists which document the effect of rate limiting and this analysis should be repeated using this new information.)

The pitch attitude dynamics of Reference 8 Configuration 2d were used as the starting point. This configuration was evaluated as a good aircraft, without PIO tendencies (PRs of 3, 2.5, and 2.5; PIORs of 2, 1, and 1). The criterion mapping for this configuration is shown in Figure 25. Note that the pilot-vehicle system with this configuration is insensitive to variations in the required tracking task acquisition time.

The first hypothetical configuration is created by adding a 25 deg/sec actuator rate limit to this nominal configuration. This configuration represents a "good" configuration with a rate-limited actuator.

The second configuration is created by adding 200 msec of pure time delay to the control system of the nominal configuration. This configuration should have poor flying qualities characteristics but no rate limiting concerns. 200 msec of delay, added to the nominal configuration, is predicted to create a Level 3 configuration in accordance with the time delay requirements of MIL-STD-1797.

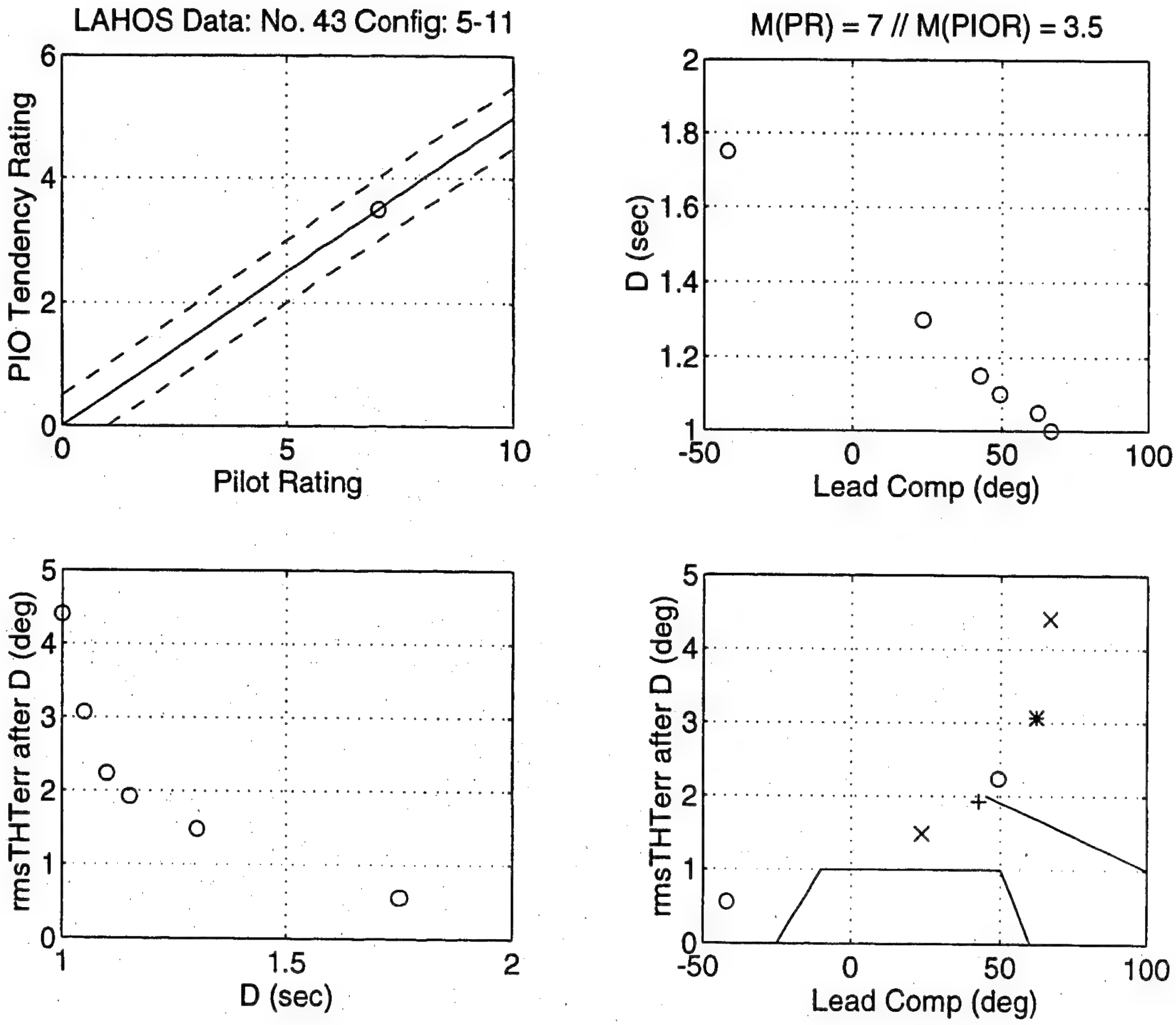


Figure 24: Configuration Mapping - Configuration 5-11 from Ref. 17

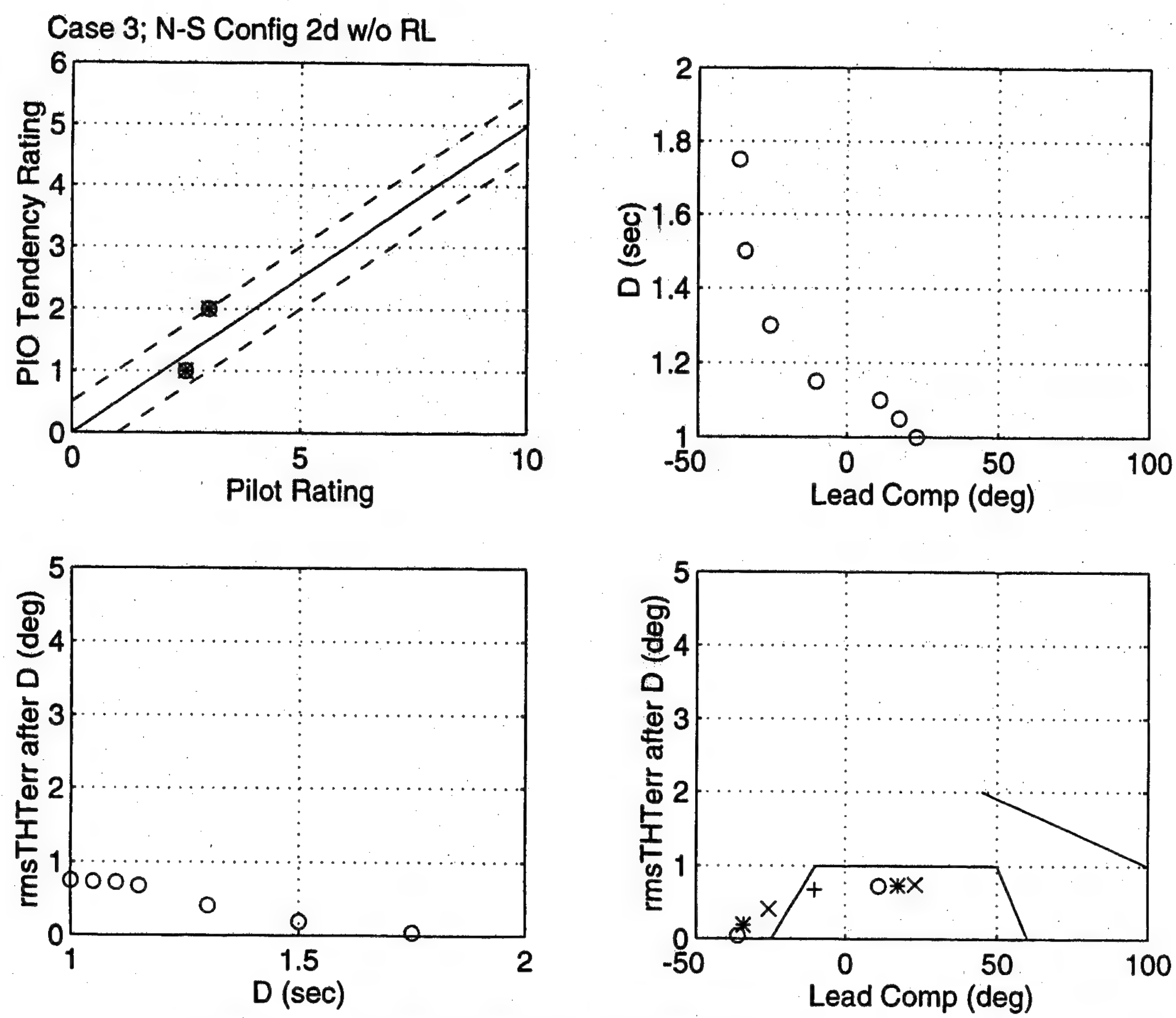


Figure 25: Criterion Mapping - Configuration 2d from Ref. 8

The third configuration adds both the 200 msec of pure delay to the control system and the 25 deg/sec rate-limited actuator to the nominal configuration. This configuration represents a Level 3 aircraft with a rate-limited actuator.

(For simplicity in this example, no control system feedback was wrapped around the rate-limited actuator, as shown in Figure 26,. Also, the additional FCS delay is not shown in this figure but it was added "up-stream" of the rate-limited actuator.)

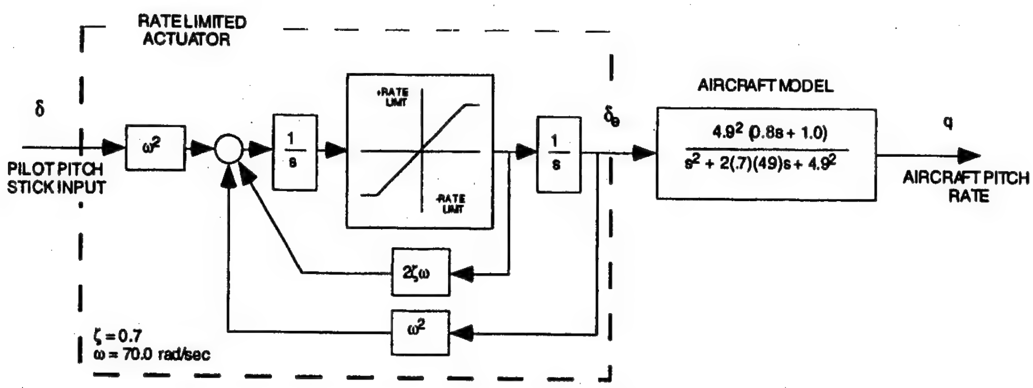


Figure 26: Rate-Limited Actuator Schematic Diagram

The analysis of the 200 msec configuration without rate-limiting is very similar to the "high-order" Neal-Smith configurations because the delay term is a "linear" PIO cause. In Figure 27, the criterion map for this configuration is shown. As the task demands increase (D drops below 1.25 sec), rms θ_e increases rapidly - indicative of PIO and the MIL-STD-predicted Level 3 handling characteristics.

The effect of rate limiting is vividly demonstrated with the configuration already degraded by 200 msec of time delay. In Figure 28, the time response of the closed-loop system is shown for an acquisition time of 1.75 sec and 1.30 sec. For the low task demands specified by 1.75 sec acquisition, the rate limit (note the control surface rate time response) is not a factor and no significant closed-loop oscillations are apparent. However, as the task demands are increased (from 1.75 sec to 1.30 sec), control surface rate limiting occurs and closed-loop oscillations in pitch attitude occur because the "pilot" is required to overdrive the vehicle to attain the required performance.

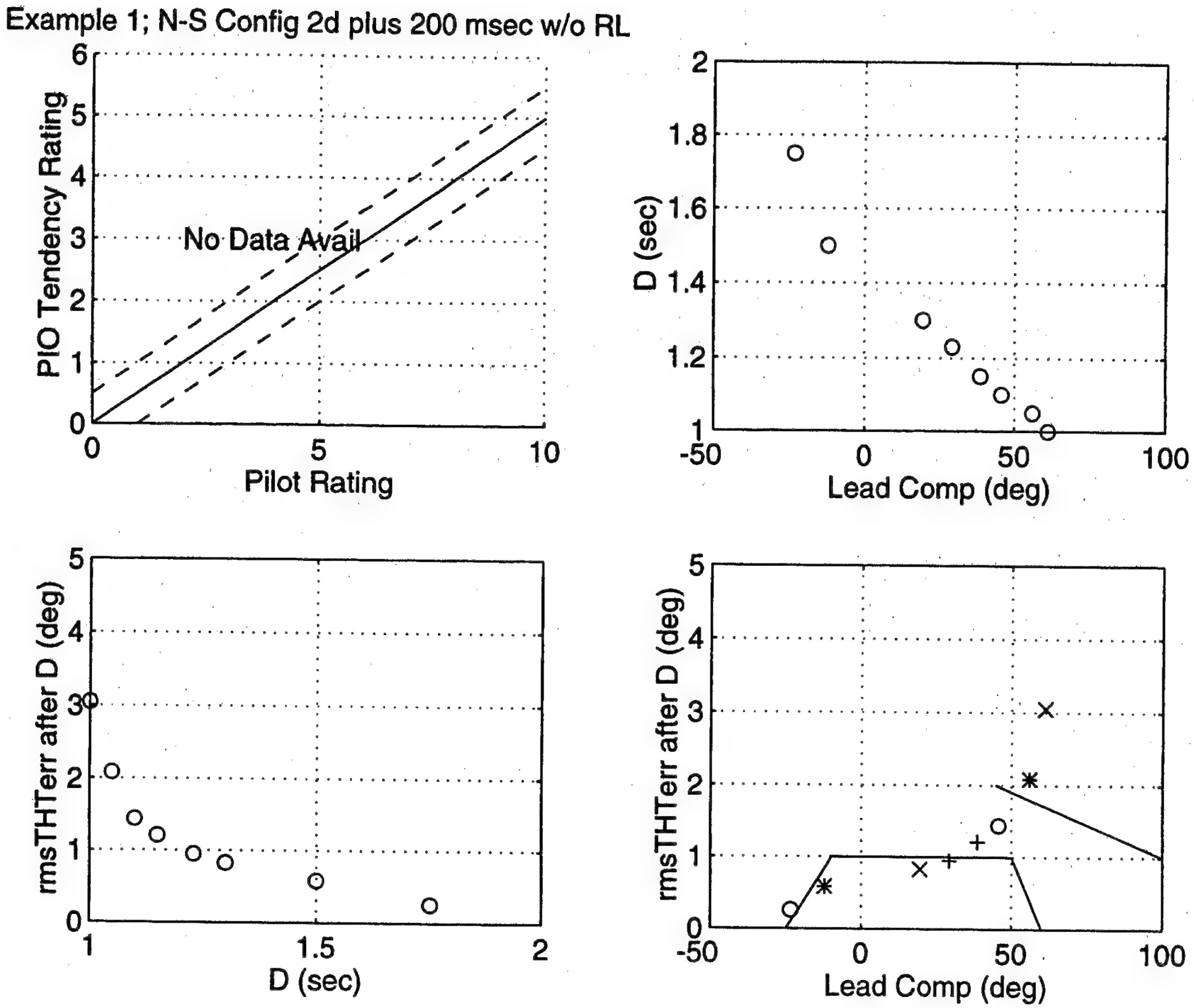


Figure 27: Criterion Mapping - Configuration 2d with 200 msec of FCS Delay

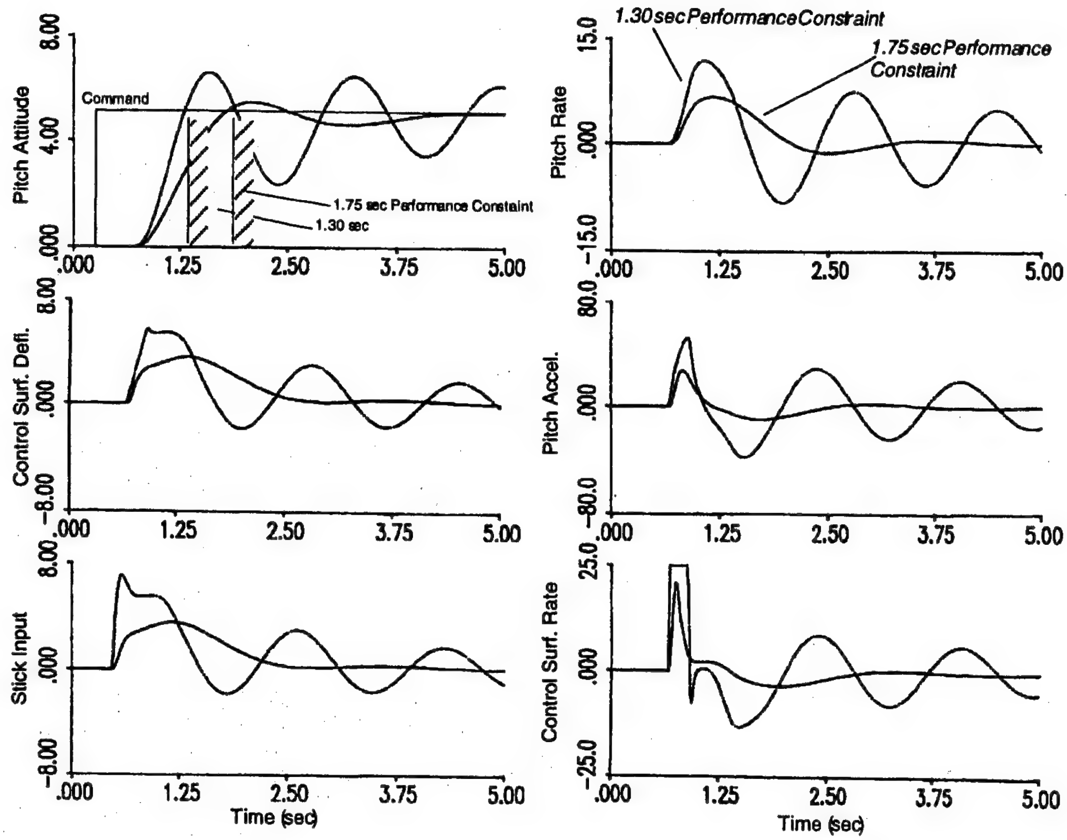


Figure 28: Closed-Loop Time Response for 25 deg/sec Rate-Limited Actuator; Configuration 2d plus 200 msec FCS Delay; D = 1.75 and 1.30 sec

The rate limiter effect is also shown in the analysis by comparing the same configuration (nominal Configuration 2d with 200 msec of FCS delay) with and without the actuator rate limiter for the same task demands. This situation is shown in Figure 29 with the required acquisition time of 1.30 sec. The rate-limited configuration response shows more oscillatory tendencies because the pilot compensator must overdrive the configuration to meet the task performance when the surface is rate-saturated.

The "explosive" effect that a rate limiter can have in degrading flying qualities and in particular, producing PIO, is demonstrated in Figure 30. For Configuration 2d with 200 msec of delay and the 25 deg/sec rate limiter, the required task urgency is increased only slightly (D to 1.23 sec from 1.30 sec). As Figure 30 clearly shows, the closed-loop response goes from slightly oscillatory for 1.30 sec of required task performance to completely unstable when 1.23 sec of task performance is demanded. With D = 1.23 sec, the control surface rate is almost always on its limit and the control surface deflection exhibits the classic saw-tooth characteristic of actuator rate-limiting. This subtle change in D pushed the closed-loop system "over the flying qualities cliff."

Again, the rate limiter effect is shown by comparison of the same configuration with and without the rate limiter using the same task performance constraint (D=1.23 sec, Figure 31). Without the rate limiter, some oscillatory behavior is noted but not to the degree that is produced with the rate-limited actuator in the closed-loop system. The rate limiter is clearly a destabilizing influence in the closed-loop.

Plotting these data on the criterion maps shows that the effect of the rate limiter is an asymptotic "barrier" where the rms θ_e explodes with very small decreases in the required task acquisition time, D (Figure 32). The pilot compensation phase angle does not change at this cliff but the closed-loop stability deteriorates rapidly. Task performance standards more stringent than the actuator rate limit-imposed cliff (i.e., shorter acquisition times) simply cannot be attained. The insidious nature of the rate-limiter is that the performance of the rate-limited and non-rate limited configurations are not significantly different for "relaxed" performance standards. Only as the rate-limiting barrier is approached is there a dramatic destabilizing effect.

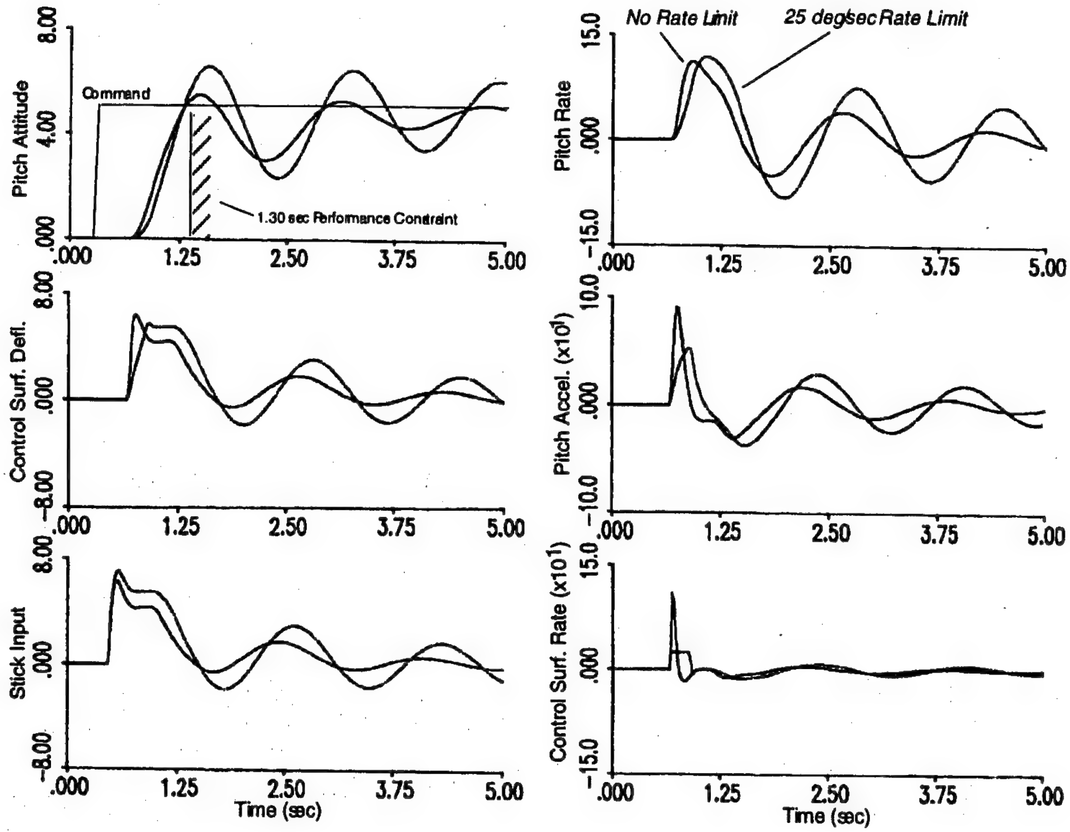


Figure 29: Closed-Loop Time Response; D = 1.30 sec; Configuration 2d with 200 msec of FCS Delay, with and without Actuator Rate Limiting

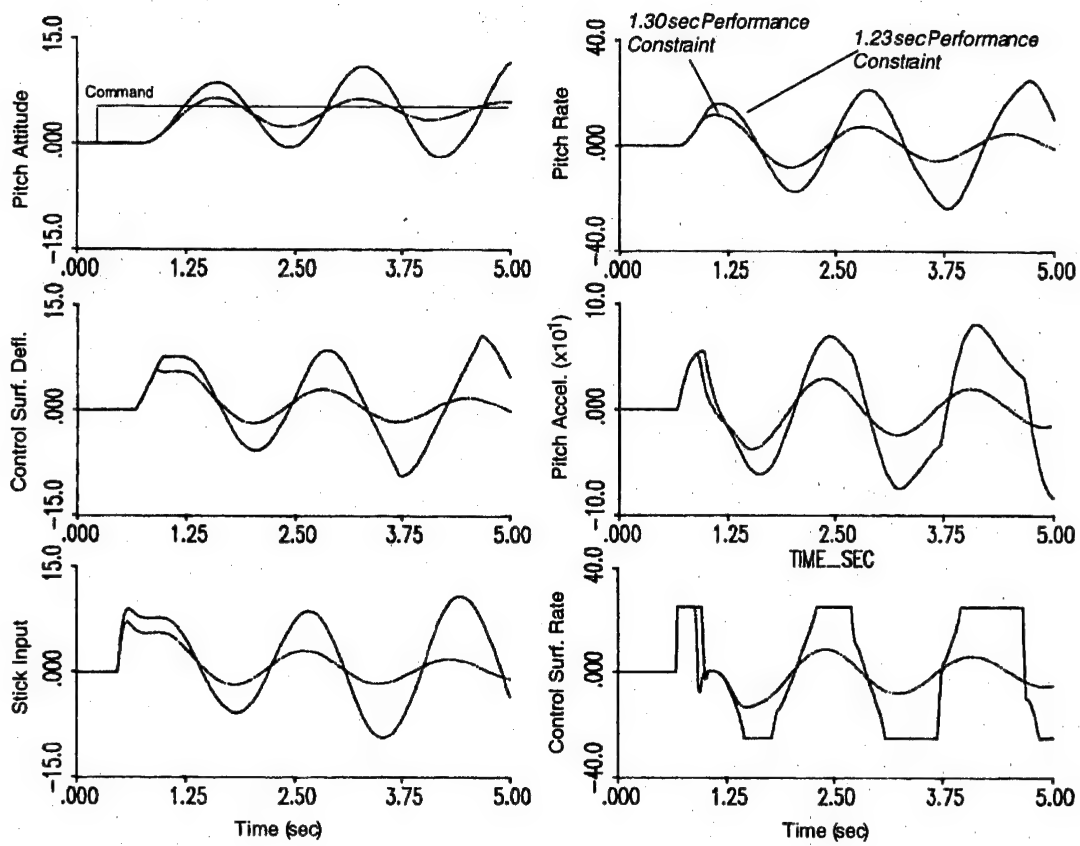


Figure 30: Closed-Loop Time Response; Configuration 2d with 200 msec of FCS Delay with Actuator Rate Limiting; D = 1.30 and 1.23 sec.

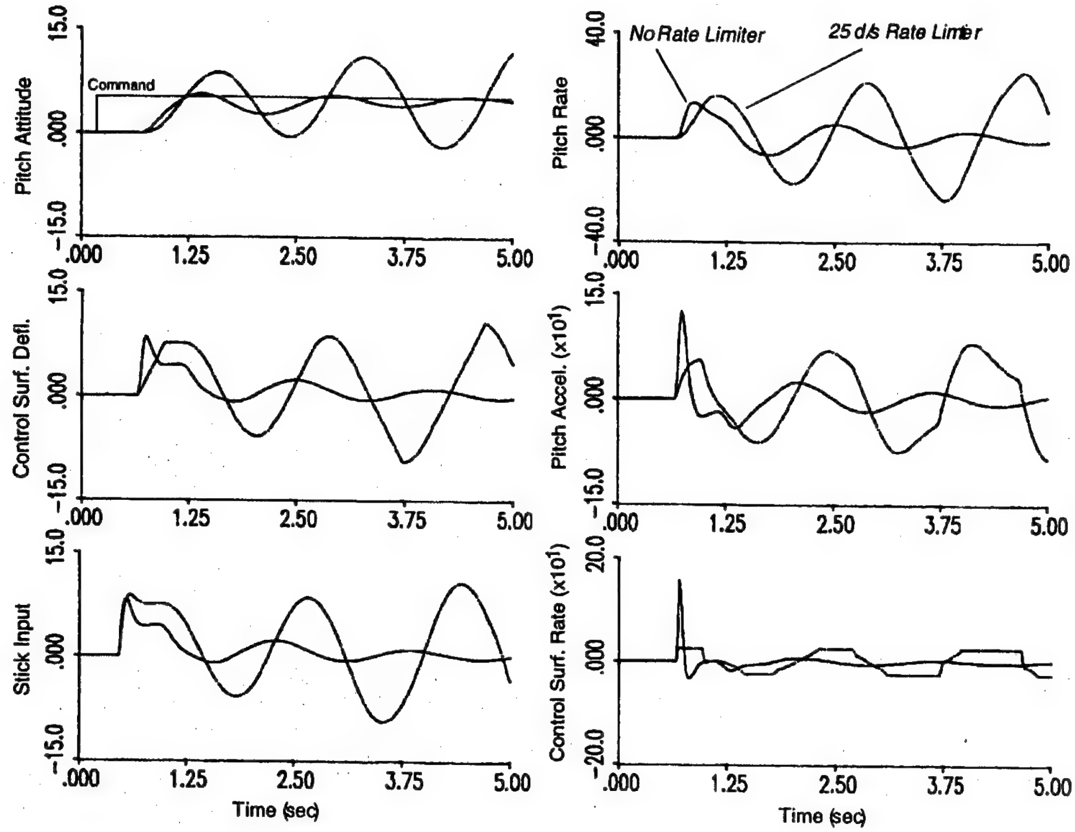


Figure 31: Closed-Loop Time Response; D = 1.23 sec; Configuration 2d with 200 msec of FCS Delay, with and without Actuator Rate Limiting

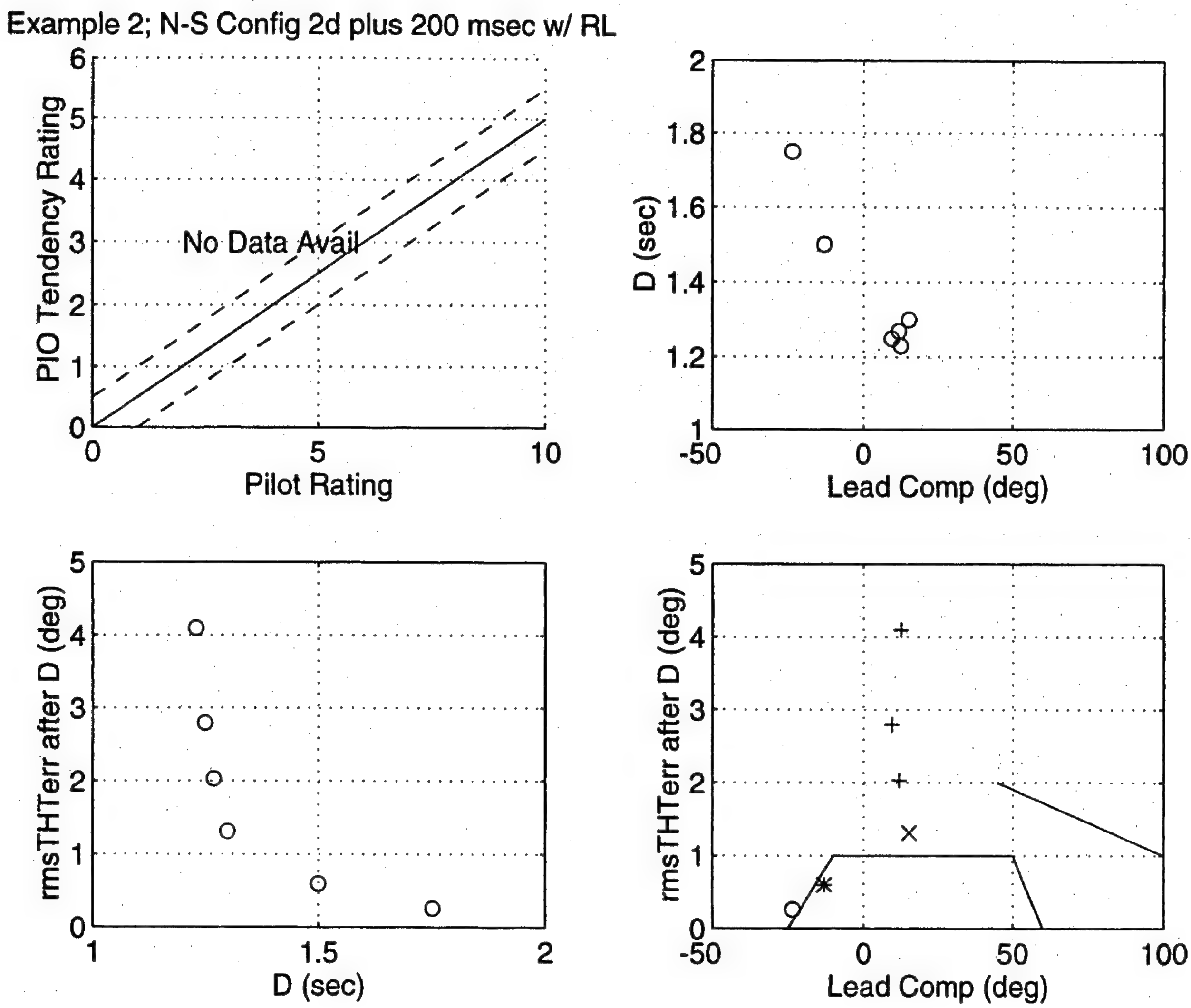


Figure 32: Criterion Map for Configuration 2d with 200 msec of FCS Delay with Actuator Rate Limiting

A criterion map, Figure 33, was also generated for the "good" configuration (nominal Configuration 2d) with the same 25 deg/sec rate-limited actuator. The effect of the rate limiter is again shown as a cliff where the rms θ_e increases greatly with very small decreases in the required task acquisition time, D (Figure 33). However, unlike Figure 32, the cliff is pushed to much higher levels of task performance bandwidth so that the pilot can get more aggressive with this configuration before reaching the cliff (i.e., smaller values of D).

This result suggests that: 1) even a configuration without significant control system delay will PIO if the rate limit is severe enough or the task performance demands placed on the configuration exceed the performance capability with the rate-limited actuator; and, 2) the effect of the control system time delay is to "move" this task performance limit to lower task bandwidths (i.e., higher values of acquisition times, D). Thus, control system time delays will exacerbate the rate-limited actuator flying qualities problems.

C.12 Proposed Quantitative PIO Metric

The quantitative PIO metric is established by:

1) quantifying the "qualitative" trends that the criterion maps indicate with respect to a configuration's PIO potential (i.e., quantifying the change in closed-loop stability (rms θ_e) with respect to the change in the required task performance, D); and,

2) realizing that the acquisition time, D, upon which a "cliff" occurs (i.e., a very large change in rms θ_e with respect to D) plays a significant role in the propensity for PIO.

There are many ways to quantify the trends witnessed qualitatively in the criterion maps. Possible metrics were evaluated based on simplicity, practicality, relevance to physical parameters, and utility in identifying PIO trends.

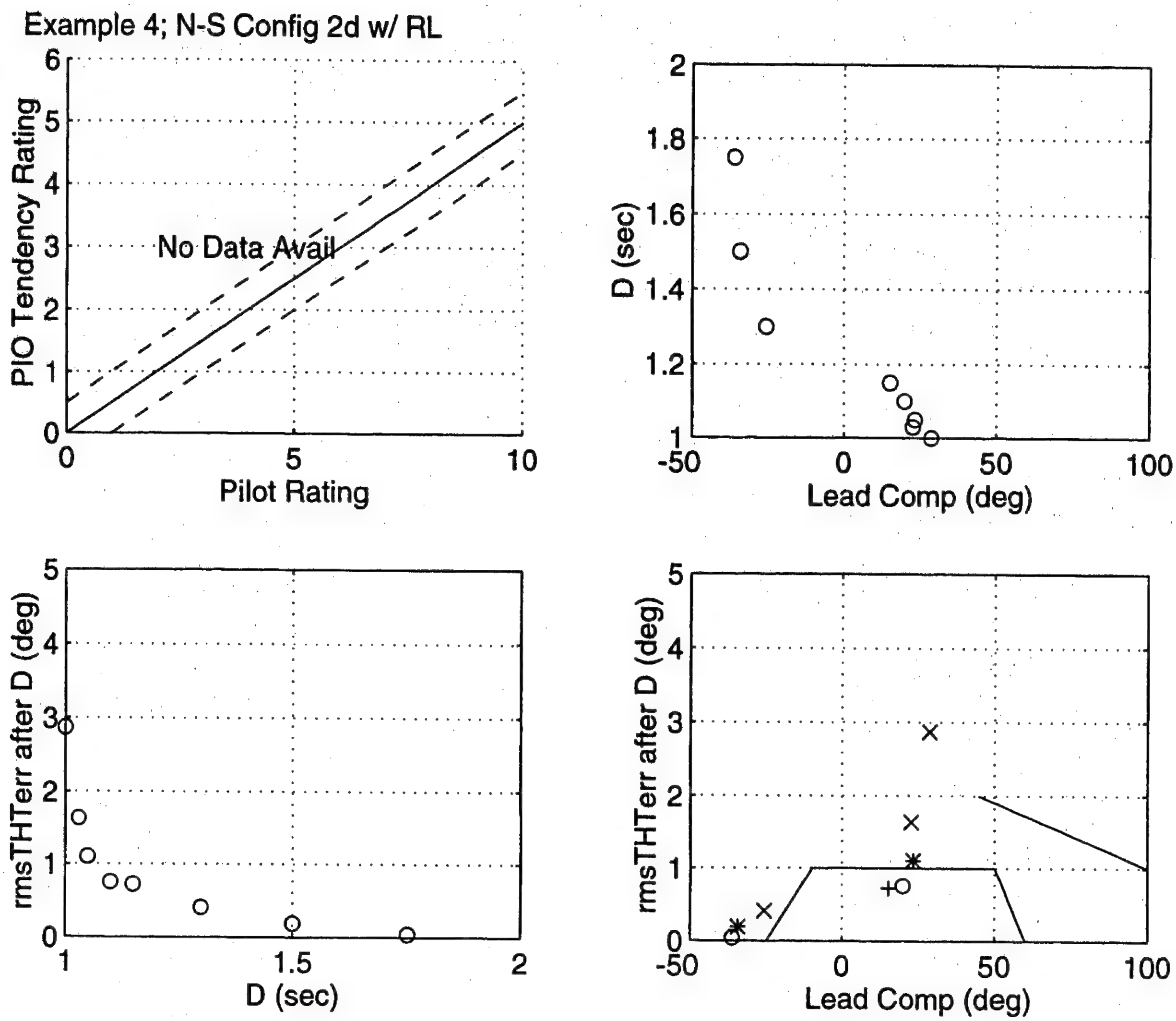


Figure 33: Criterion Map for Configuration 2d with Actuator Rate Limiting

The best quantifying metric for PIO, to date, was determined from the second derivative of the rms θ_e with respect to D. The hypothesis in using the second derivative is that it relates to where the "break" in the closed-loop stability occurs with respect to the task performance requirement. This metric is assumed to be a necessary condition for the PIO criterion as shown in the following.

A secondary ingredient is the time, D, for which this break point occurs. Unfortunately, this metric has not yet been incorporated into the criterion. However, the rate-limited actuator examples highlight the importance of this term. A proposed criterion using this quantity is left for future work.

As the configuration maps in Appendix D show, the criterion was calculated for several values of D, ranging from 1.75 sec down to 0.90 sec. These values were chosen somewhat arbitrarily due to the "exploratory" or developmental nature of the criterion. A future initiative would change the algorithm mechanics so that a "complete" sweep of required task constraints, D, was executed for each configuration rather than a select few. This way, a smooth mapping would be obtained.

In lieu of this procedure, the second derivative at the required task performance value of D (D_2 in this nomenclature) was computed by discrete approximation as:

$$\frac{d^2\left(\mathrm{rms}\theta_e|_{D_2}\right)}{dt^2} \cong \frac{\left(\mathrm{rms}\theta_e|_{D_1} + \mathrm{rms}\theta_e|_{D_3} - 2\ \mathrm{rms}\theta_e|_{D_2}\right)}{\Delta T^2}$$

where

$\dfrac{d^2\left(\mathrm{rms}\theta_e|_{D_2}\right)}{dt^2}$ is the approximate (local) second derivative of the rms θ_e (after D) with respect to D at the point D_2; and

D_1 and D_3 are values of D greater than and less than D_2 by ΔT; i.e., $D_1 = D_2 - \Delta T$ and $D_3 = D_2 + \Delta T_1$.

The values of the approximate second derivative of the rms θ_e vs. D criterion outputs are plotted in Appendix F for each configuration in the Reference 8, 17, and 18 data bases. Inspection of these plots indicates that the lack of more finely-spaced criterion outputs hinders the interpretation and pinpoint precision of the results because of the discrete, noisy character of the computed second derivative. However, the results are quite reasonable and they demonstrate the potential of the analysis technique.

The technique is illustrated in Figure 34. For each configuration mapping, the local second derivative was computed for each chosen value of D. The second order derivative reflects the concavity of the rmsθ_e versus D plot - that is, the second derivative provides a quantification of the degree in which the rmsθ_e "bends" with respect to D (e.g., the steepness of the handling qualities "cliff").

A value of 100 for the second derivative was chosen as the PIO metric.

- If a value of $d^2(\text{rms}\theta_e)/dt^2\big|_{D_2}$ exceeded 100, the configuration was categorized as being PIO-prone.
- If the values of $d^2(\text{rms}\theta_e)/dt^2\big|_{D_2}$ remained below 100, the configuration was considered to be PIO-immune.

This relationship is illustrated in Figure 34 for two example Neal-Smith configurations. The value of $d^2(\text{rms}\theta_e)/dt^2\big|_{D_2}$ reflects the concavity of the rmsθ_e curve. (Note that the PIO criterion plots on the right-hand side of the figure use a logarithmic scale for the vertical axis.) It is proposed as a measure of the PIO tendency of a configuration. The value of D for which this PIO threshold was "first" exceeded (i.e. the maximum value of D) was noted since it is felt that this is an important PIO parameter, though it is not included here due to the lack of substantiating work. However, at this time, is assumed to be an important parameter because it qualifies the value of D at which the PIO will be evident to the pilot compared to the value of D which is the task performance standard, such as those used in the flying qualities analyses shown in Figures 17-20.

C.13 Proposed PIO Metric Compared to Neal-Smith Data Base

Using this PIO metric, the data of Reference 8 were evaluated.

In Table I, those configurations that did not have values of $d^2(\text{rms}\theta_e)/dt^2\big|_{D_2}$ which exceeded the threshold value of 100 are listed. These configurations are predicted to be PIO – immune by the proposed quantitative PIO criterion. The table gives the configuration identifier, the

individual PRs and PIORs for the configuration, the least constraining time (i.e., maximum value of D_2, in which the value of $d^2(\text{rms}\theta_e)/dt^2\big|_{D_2}$ exceeded the threshold), and the maximum value of the second derivative across all values of D. (Of course, for Table I, the time at which the second derivative exceeds the threshold is not applicable (n/a) since, by definition of the table, these configurations never exceeded this value for the computed D values).

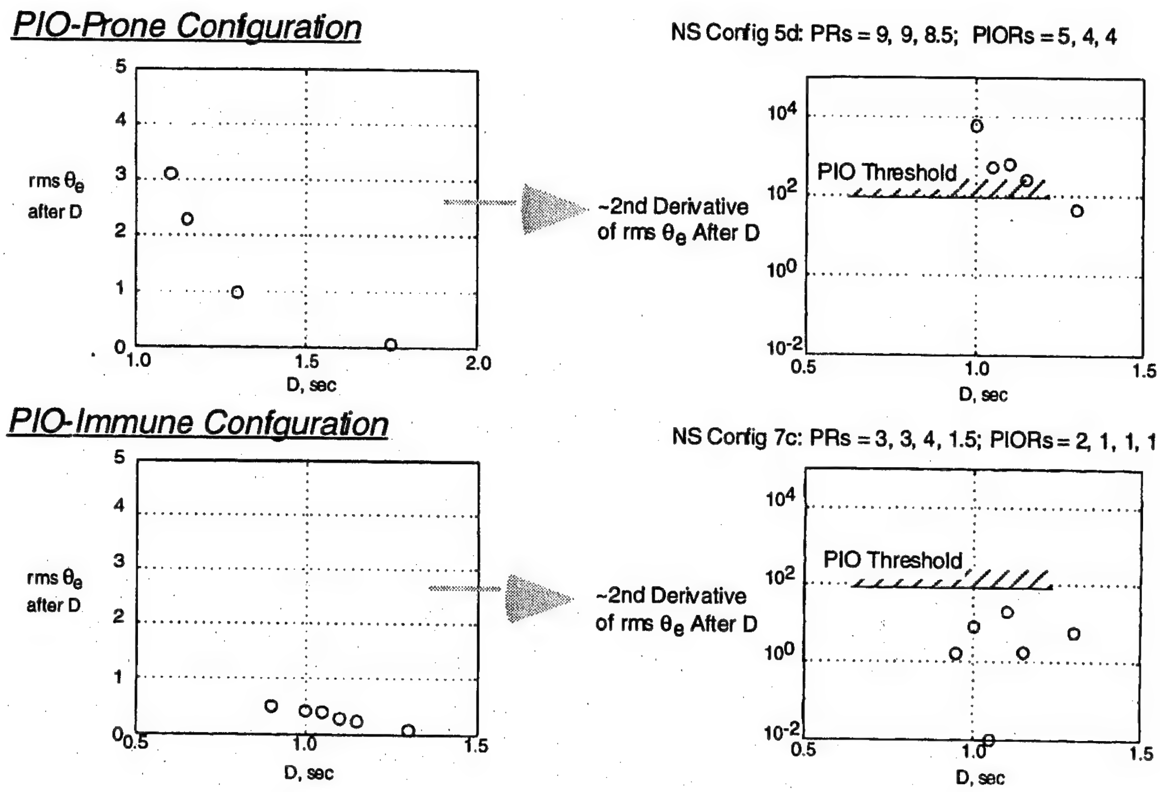


Figure 34: PIO Metric Computation Example

Table I

Predicted PIO-Immune Configurations - Neal-Smith Data Base

a) Configurations with Maximum Second Order Derivative <100 and PR < 6.5 and PIOR ≤ 3

No.	Config	Median PR	Median PIOR	PRs	PIORs	Max D for (-) > 100	Max Value
1	1a	5	2	6, 4, 5	2.5, 1.5, 2	n/a	14.8
2	1b	3.25	1.25	3.5, 3	1, 1.5	n/a	13.6
3	1c	4	2	5, 3.5, 4	2.5, 2, 1.5	n/a	66.4
4	1d	4.25	2	5, 4.5, 3, 4	2.5, 2, 1, 2	n/a	24.0
8	2a	4.25	2	4.5, 4	2, 2	n/a	37.2
9	2b	5.5	2.5	6, 6, 4, 5	2.5, 3, 1.5, 2.5	n/a	65.6
10	2c	3	1.5	3	1.5	n/a	25.2
11	2d	2.5	1	3, 2.5, 2.5	2, 1, 1	n/a	14.0
12	2e	4	1	4	1	n/a	62.4
18	3a	4	1.5	5, 4, 4, 4	3, 1.5, 1, 1.5	n/a	38.0
19	3b	4.5	2	4.5	2	n/a	32.0
20	3c	3.5	1.5	4, 3	2, 1	n/a	28.8
21	3d	4	1.5	4, 4	2, 1	n/a	35.6
22	3e	4	1.25	4, 4	1.5, 1	n/a	28.8
33	6a	5.5	2.5	5, 6	2, 3	n/a	14.4
34	6b	2.5	1.5	2.5, 1, 4	1.5, 1, 1.5	n/a	14.4
35	6c	4.5	2.25	4, 5	2.5, 2	n/a	26.0
39	7a	4	2	5, 4, 2	2, 2, 1	n/a	45.2
40	7b	3	1.5	3	1.5	n/a	30.8
41	7c	3	1.5	3, 3, 4, 1.5	2, 2, 1, 1	n/a	19.6
42	7d	5.5	3	5.5	3	n/a	23.6
43	7e	5.5	2.5	6, 5	3, 2	n/a	45.6
45	7g	5.5	2	5, 6	2, 2	n/a	86.0
46	7h	5	2	5	2	n/a	92.0
47	8a	4.5	1.75	5 ,4	2.5, 1	n/a	16.8
48	8b	3.5	1.5	3.5	1.5	n/a	24.4
49	8c	3.25	1.5	3.5, 3	2, 1	n/a	17.2
50	8d	3	1.5	2, 4	1, 2	n/a	14.8
51	8e	3	1	2.5, 3, 5	1, 1, 2	n/a	7.2

*Configuration with Max Value of D for second derivative > 100 is also Time for Maximum Second Derivative Value

b) Configurations with Maximum Second Order Derivative <100 and PR ≥ 6.5 or PIOR > 3

No.	Config	Median PR	Median PIOR	PRs	PIORs	Max D for > 100	Max Value
44	7f	5.5	2.75	3, 4, 4, 7, 7, 7	2, 2, 2, 3.5, 4	n/a	74.8

*Configuration with Max Value of D for second derivative > 100 is also Time for Maximum Second Derivative Value

Table I is broken into two parts: a) those configurations for which *all* PRs were less than 6.5 and *all* PIORs were less than or equal to 3; and, b) those configurations for which *any* PRs were greater than or equal to 6.5 or *any* PIORs were greater than 3.

For group (a), these configurations are considered to be successes - these configurations did not exceed the PIO threshold value for $d^2(rms\theta_e)/dt^2\big|_{D_2}$ and the pilot rating data indicates that, indeed, neither PIO-prone nor deficient flying qualities data were given to these configurations.

For group (b), these configurations are failures - these configurations were computed by the criterion to be PIO-immune, yet the evaluation data suggests that deficient flying qualities or PIO-potential are actually present. For the Reference 8 data base, only one configuration was a failure (Configuration 7f - which was rated dichotomously by Pilot W and Pilot M - see Ref. 8).

In Table II, those configurations that have values of $d^2(rms\theta_e)/dt^2\big|_{D_2}$ which exceeded the threshold value of 100 are listed. These configurations are predicted to be PIO-prone by the proposed quantitative criterion. The table gives the configuration identifier, the individual PRs and PIORs for the configuration, and the least constraining time, D_2, in which the value of $d^2(rms\theta_e)/dt^2\big|_{D_2}$ exceeded the threshold and the maximum value of the second derivative across all values of D.

This table is again broken into two parts: a) those configurations for which *all* PRs were less than 6.5 and *all* PIORs were less than or equal to 3; and, b) those configurations for which *any* PRs were greater than or equal to 6.5 or *any* PIORs greater than 3.

Table II

Predicted PIO-Prone Configurations – Neal-Smith Data Base

a) Configurations with Maximum Second Order Derivative >100 and PR < 6.5 and PIOR ≤ 3

No.	Config	Median PR	Median PIOR	PRs	PIORs	Max. D for >100	Max Value
13	2f	3	1	3	1	1.00*	187.6
15	2h	5.5	2.5	5, 6, 5.5	2.5, 2.5, 2	1.00*	337.2
17	2j	6	2	6, 6	2, 2	1.00*	430.0
23	4a	5.25	2.25	5.5, 5	2.5, 2	1.00*	105.2
36	6d	5.5	2.5	5.5	2.5	1.00*	272.4

*Configuration with Max Value of D for second derivative > 100 is also Time for Maximum Second Derivative Value

b) Configurations with Maximum Second Order Derivative >100 and PR ≥ 6.5 or PIOR > 3

No.	Config	Median PR	Median PIOR	PRs	PIORs	Max. D for > 100	Max Value
5	1e	6	3.5	6	3.5	1.10	882.4
6	1f	8	4	8, 8	4, 4	1.15	3212.0
7	1g	8.5	4.25	8.5, 8.5	4.5, 4	1.15	11883.6
14	2g	7	3	7	3	1.10	1488.0
16	2i	8	4.25	8, 8	4.5, 4	1.15	2862.8
24	4b	7	4	7	4	1.10	725.2
25	4c	8.5	4	8.5	4	1.15	1435.2
26	4d	8.5	4.25	8, 9	3.5, 5	1.15	2833.2
27	4e	7.5	4	7.5	4	1.15	2550.0
28	5a	6	3	7, 5, 6	3, 1.5, 3	1.00*	158.8
29	5b	7	4	7	4	1.30	1770.0
30	5c	8	4.5	9, 7	5, 4	1.15	2902.0
31	5d	9	4	8.5, 9, 9	4, 5, 4	1.15	5829.6
32	5e	8	4	8, 8	4, 4	1.15	4841.2
37	6e	7.75	4.5	8.5, 7	5, 4	1.10	1246.0
38	6f	8.5	4	8, 8.5, 10	4 ,4, 5	1.15	5842.0

*Configuration with Max Value of D for second derivative > 100 is also Time for Maximum Second Derivative Value

Notes:

1) Ratings taken from Table I of AFFDL-TR-70-74.
2) Additional position command system configurations not used in analysis because of sparse rating data.
3) Ratings which were identified as anomalous by the authors were not used in the summary.

In this case, group (b) configurations are considered to be successes for the proposed criterion - these configurations did exceed the PIO threshold value for $d^2(\mathrm{rms}\theta_e)/dt^2\big|_{D_2}$ and the pilot rating data indicates that, indeed, PIO-tendencies or deficient flying qualities were witnessed by the pilots for these configurations.

Group (a) configurations are predicted overly conservatively by the criterion. They are not failures per se, rather, the criterion predicts PIO problems but the flight test data indicates otherwise. Failure in criterion viability is associated with those configurations that "pass" the criterion but are, in actuality, PIO-prone (these were presented above). This failure situation can be a serious problem since the designer can be given a false sense of "flying qualities security." Conversely, the conservative scenario (i.e., predicted PIO-prone but PIO-free in actuality) is not necessarily desired either, but it is more tractable. However, the criterion should not be so conservative that *too many* configurations are deemed to be PIO-prone when in fact they are not - that scenario is analogous to the "boy who cried wolf," and it results in the criterion being ignored.

Five configurations were found in group (a) where the criterion considered them to be PIO-prone while the flight evaluation data suggests that deficient flying qualities or PIO-potential were not actually present. Four of the configurations were multiply-rated to be high-Level 2 (PRs ~ 5 to 6 or marginally bad) and the remaining configuration was only rated once. None of these prediction "misses" was considered to be severe enough to warrant invalidation of the PIO threshold.

Trends of the maximum values of D for which the PIO threshold is exceeded and the maximum values for the second derivative were noted. However, the data and analysis to date was felt to be insufficient to draw conclusions. These results are tabulated but additional work is warranted to evaluate the utility of these parameters as potential PIO conditions.

C.14 Proposed PIO Metric Compared to LAHOS Data Base

Using this PIO metric, the data of Reference 17 were evaluated.

In Table III, those configurations that did *not* have values of $d^2(\mathrm{rms}\theta_e)/dt^2\big|_{D_2}$ which exceeded the threshold value of 100 are listed. These configurations are predicted to be PIO-immune by the proposed quantitative PIO criterion. The table gives the configuration identifier, the

Table III

Predicted PIO-Immune Configurations - LAHOS Data Base

a) Configurations with Maximum Second Order Derivative <100 and PR < 6.5 and PIOR ≤ 3

No.	Config	Median PR	Median PIOR	PRs	PIORs	Max D for >100	Max Value
1	1-a	6	1	6	1	n/a	0.1
2	1-b	5	2	5	2	n/a	0.8
3	1-c	4	1	4	1	n/a	3.2
4.	1-1	4	1.5	4, 4	2, 1	n/a	12.0
5	1-2	5	2	5	2	n/a	48.4
8	1-6	5	2	5	2	n/a	54.8
11	2-a	5	2.25	4,6	2, 2.5	n/a	0.8
12	2-c	2.25	1	4, 1.5, 1.5, 2	2, 1, 1, 1	n/a	0.8
13	2-1	2	1	2,2	1,1	n/a	8.0
14	2-2	4.25	1.5	4.5, 4	1, 2	n/a	44.8
17	2-6	5	2.5	5	2.5	n/a	54.4
22	3-c	3.5	1.25	2, 5	1, 1.5	n/a	0.8
23	3-0	4.5	1.5	4, 5	1, 2	n/a	8.4
29	4-c	3	1.75	3, 3	1.5, 2	n/a	2.4
30	4-1	2	1	2	1	n/a	7.2
33	4-6	4	2	4	2	n/a	33.2
34	4-7	3	1	3	1	n/a	57.6
41	5-6	6	3	6	3	n/a	46.4
42	5-7	6	3	6	3	n/a	91.6
45	6-2	2	1	2	1	n/a	10.4

*Configuration with Max. Value of D for second derivative > 100 is also Time for Maximum Second Derivative Value

b) Configurations with Maximum Second Order Derivative <100 and PR ≥ 6.5 or PIOR > 3

No.	Config	Median PR	Median PIOR	PRs	PIORs	Max. D for >100	Max Value
24	3-1	5	2	4, 5, 7	2, 2, 3	n/a	8.4
25	3-2	7	3	7	3	n/a	79.6
27	3-6	6.5	3	7, 6	3, 3	n/a	96.4
31	4-3	7	3	5, 7, 8	2, 3, 3	n/a	75.6
37	5-1	6	3	7, 5	3, 3	n/a	5.6

*Configuration with Max. Value of D for second derivative > 100 is also Time for Maximum Second Derivative Value

individual PRs and PIORs for the configuration, and the least constraining time, D, in which the value of $d^2(\mathrm{rms}\theta_e)/dt^2\big|_{D_2}$ exceeded the threshold and the maximum value of the second derivative across all values of D. (Of course, for Table III, the time at which the second derivative exceeds the threshold is not relevant since, by definition, these configurations never exceeded this value for the computed D values).

Again, the table is broken into two parts: a) those configurations for which *all* PRs were less than 6.5 and *all* PIORs were less than or equal to 3; and, b) those configurations for which *any* PRs were greater than or equal to 6.5 or *any* PIORs were greater than 3.

Group (a) configurations are considered to be successes for the criterion - these configurations did not exceed the PIO threshold value for $d^2(\mathrm{rms}\theta_e)/dt^2\big|_{D_2}$ and the pilot rating data indicates that, indeed, neither PIO-prone nor deficient flying qualities ratings were given to these configurations.

Group (b) configurations are failures of the criterion - these configurations were computed by the criterion to be PIO-immune, yet the evaluation data suggests that deficient flying qualities or PIO-potential are actually present. The analysis failed to properly identify five configurations.

Three of these configurations were "lightly damped" configurations. These cases do not warrant revision to the PIO threshold criterion because low short period damping is not a typical problem in fly-by-wire flight control system design (the focus of this endeavor).

Configuration 5-1 was not considered by the PIO criterion to be PIO-prone, but a Level 3 pilot rating was given to this configuration during its flight testing. The pilot comments noted "abruptness" in the aircraft response. This PIO criterion emphasizes (rightly or wrongly) the effects of augmented aircraft lags or delays which contribute to PIO. It is not intended nor is it "equipped" at this time to identify PIO which is due to excessive command gain (i.e., oversensitivity). The pilot model in the criterion can employ "infinite" or "infinitesimal" gain to "close-the-loop." (The effects of command gain and nonlinear command gradients have not been investigated with the criterion and it is not clear what insight may be gained from application of this criterion for that particular design problem.)

In Table IV, those LAHOS configurations that have values of $d^2(\mathrm{rms}\theta_e)/dt^2\Big|_{D_2}$ which exceed the threshold values of 100 are listed. These configurations are predicted to be PIO prone.

Again, the table is broken into two parts: a) those configurations for which *all* PRs were less than 6.5 and *all* PIORs were less than or equal to 3; and, b) those configurations for which *any* PRs were greater than 6.5 or *any* PIORs greater than 3.

Table IV

Predicted PIO-Prone Configurations - LAHOS Data Base

a) Configurations with Maximum Second Order Derivative >100 and PR < 6.5 and PIOR ≤ 3

No.	Config	Median PR	Median PIOR	PRs	PIORs	Max D for >100	Max
15	2-3	6	3	6	3	1.15*	155.6
39	5-4	6	2.5	6	2.5	1.10*	200.0

*Configuration with Max. value of D for second derivative > 100 is also Time for Maximum Second Derivative Value

b) Configurations with Maximum Second Order Derivative >100 and PR ≥ 6.5 or PIOR > 3

No.	Config	Median PR	Median PIOR	PRs	PIORs	Max D for >100	Max
6	1-3	9.5	4	9, 10	4, 4	1.10	220.4
7	1-4	10	4	10	4	1.15	696.8
9	1-8	8	3	8	3	1.15	316.4
10	1-11	9	3.5	9	3.5	1.10	348.0
16	2-4	9	3	9	3	1.15	312.0
18	2-7	6.5	3	7, 6	3, 3	1.10*	111.2
19	2-9	10	3	10	3	1.15	2200.0
20	2-10	10	4	10	4	1.30	10408.0
21	2-11	8	3	8	3	1.15	384.8
26	3-3	10	4	10	4	1.15	349.2
28	3-7	8	4	8	4	1.10	258.4
32	4-4	6.5	3	7, 6	3, 3	1.10*	150.0
35	4-10	9	4	9	4	1.30	4912.0
36	4-11	8	4	8	4	1.10*	120.8
38	5-3	6	3	8, 4.5, 6	3, 2.5, 3	1.10*	120.4
40	5-5	7	3	7	3	1.10*	212.0
43	5-11	7	3.5	7	3.5	1.10*	207.2
44	6-1	10	4	10	4	1.30	7512.0

* Configuration with Max. value of D for second derivative > 100 is also Time for Maximum Second Derivative Value

Group (b) configurations are considered to be successes for the criterion - these configurations did exceed the PIO threshold value for $d^2(\mathrm{rms}\theta_e)/dt^2|_{D_2}$ and the pilot rating data indicates that, indeed, PIO-tendencies or deficient flying qualities were witnessed by the pilots for these configurations.

Group (a) configurations are conservatively predicted (i.e., PIO tendencies are predicted but none were found in flight test).

The configurations in group (a) (2 configurations in total) were computed by the criterion to be PIO-prone; however, the evaluation data suggests that deficient flying qualities or PIO-potential are not actually present. None of these prediction "misses" was considered to be severe enough to warrant invalidation of the PIO threshold because the pilot ratings were 6's (marginally acceptable) and only one evaluation was given for each configuration.

Again, trends about the maximum value of D for which exceeded the PIO threshold was exceeded and the maximum values of the second derivative were noted but data and analysis to date was felt to be insufficient to draw conclusions.

C.15 Proposed PIO Metric and Rate-Limited Actuator Configurations

The hypothetical configurations used to evaluate rate limiting effects on flying qualities with the Time Domain Neal-Smith criterion were compared to the proposed quantitative PIO criterion.

In Figure 35, the second derivative values are plotted for the four configurations as the task constraint, D, was varied. The upper left hand plot shows that the nominal configuration (configuration 2d) is predicted to be non-PIO-prone. The value of the second derivative for this configuration remains below the criterion limit of 100.

With 200 msec of delay added to this configuration, the upper right hand plot shows that this configuration would be predicted to exhibit PIO tendencies. A value of 100 is exceeded as D approaches 1.10 sec.

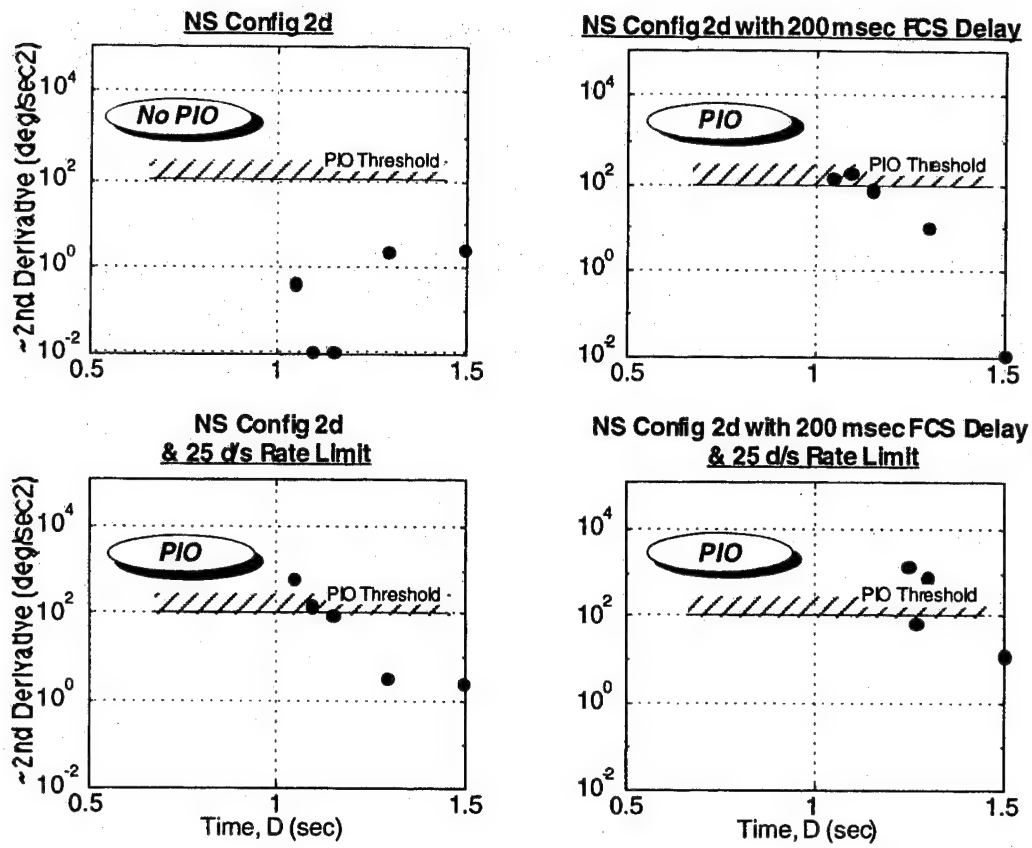


Figure 35: PIO Metrics Compared to Rate-Limited Actuator Configurations

The lower right- and left-hand plots show that the rate-limited actuator creates configurations that are predicted to be PIO prone. The significant difference between these two configurations is that the rate-limited configuration with 200 msec of added delay will exhibit PIO tendencies at significantly lower task bandwidths (D of approximately 1.25 sec) than the nominal configuration with rate limited actuator but no additional delay (D of approximately 1.05 sec). This comparison highlights how the time, D, in which the PIO threshold is exceeded may be an important PIO parameter. These values were included in the configuration tables (Tables I-IV) but more data are needed to formulate conclusions.

C.16 Quantitative PIO Summary

In summary, a quantitative PIO measure has been developed along with a supporting methodology, analysis procedures, and tools. The results are encouraging in that the vast majority of PIO-prone configurations from two flying qualities data bases were successfully identified using

the proposed criterion. Very few "failures" were noted (i.e., instances where the criterion does not predict PIO tendencies but, in actuality, there are) and the criterion was not so conservative that the criterion would be ignored (i.e., few instances where PIO tendencies were predicted but, in actuality, there were none).

Evaluation of rate-limited actuator effects on flying qualities was also shown. The proposed technique clearly demonstrated proper analysis of the flying qualities effects due to rate limiting.

D. Simulation

Simulation testing (i.e., pilot-in-the-loop ground simulation) should include target acquisition and tracking tasks which can be compared to the analytical models and procedures outlined here. By comparative analysis, insight into the configuration flying qualities, pilot control techniques, and PIO potential can be gained that would otherwise not be obtainable without this analysis.

Tasks that are amenable to this form of analysis include:

1) Target tracking tasks (Reference 22)

2) HUD tracking tasks (Reference 21 and 23)

3) Go-around and pitch takeoff rotation tasks to pre-defined attitude references

4) Ground attack pitch acquisition tasks such as those provided by ATLAS (Adaptable Target Lighting Array System, Reference 24).

Simulation testing can be used for comparison to the PIO analysis predictions with each of these tasks. The actual and predicted pilot control techniques and closed-loop aircraft responses can be compared (i.e., time history comparison) to provide insight into the effects of ground simulator characteristics (motion, visual, and tactile cues).

The Time Domain Neal-Smith criterion should incorporate mission relevance with the selection of the step input command sizes and the allowable pipper errors. The analysis methods can be made to correlate directly to the planned addition of evaluation tasks in MIL-STD-1797.

The designer will then have an analysis tool to complement the pilot-in-the-loop flight/simulation testing requirements of MIL-STD-1797.

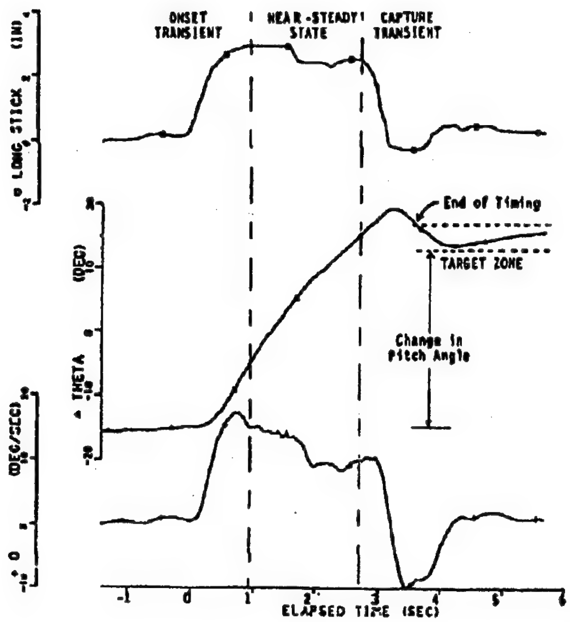
E. Flight Test

The step target tracking task holds a perfect analogy with respect to aircraft design, test and evaluation from the aircraft "agility" metrics development that has been on-going with the USAF (e.g., Reference 25).

The same "maneuver" used in the Time Domain Neal-Smith criterion (i.e., the attitude command acquisition task) has been proposed as an aircraft agility metric (Reference 25). An example of the Agility Metric is shown in Figure 36. Significant flight testing was conducted to determine the utility of the maneuver for agility work and the results were very favorable. A significant compilation of flight test data investigating this step attitude target tracking task is available for different aircraft, variations in testing techniques, and different flight conditions. The "ELAPSED TIME" and "DELTA THETA" shown in Figure 36 are, respectively, analogous to the required acquisition time, D, and the step pitch attitude target, θ_c, definitions in the Time Domain Neal-Smith criterion.

This flight test task combined with the analytical tool (using the same "task") can provide significant insight into aircraft agility *and* pilot controllability. This analysis is a perfect complement since pilot controllability was a missing "ingredient" in the agility work, but now this ingredient is available. Also, the required value of acquisition time, D, in the Neal-Smith criterion can be tied to aircraft performance and mission requirements.

With appropriate resources, there should be no limitations (other than safety-of-flight) that would restrict flight testing using the same tasks that were performed in ground simulation. This way, the Time Domain Neal-Smith analysis can be used throughout simulation testing and flight testing as an analytical tool to complement the actual pilot-in-the-loop testing.



Agility Maneuver Segments

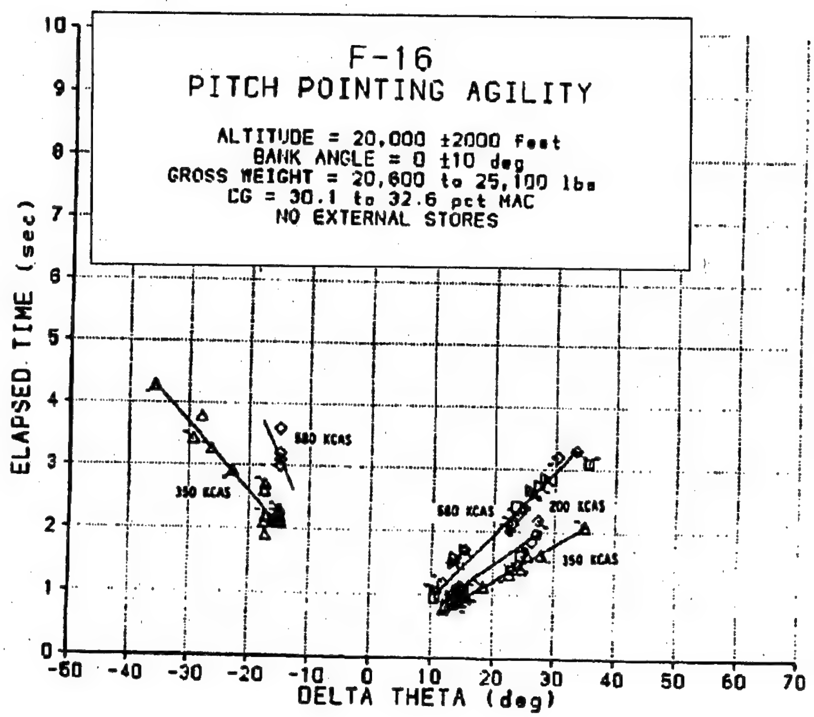


Figure 36: Agility Metrics Analog to Time Domain Neal-Smith Criterion Task (taken from Reference 25)

Section 5.0
CONCLUSIONS AND RECOMMENDATIONS

A Time Domain Neal-Smith criterion was developed to form the basis for a quantitative PIO metric. The criterion is a pilot-in-the-loop test formulated in the time domain using a step attitude target tracking task.

The Time Domain Neal-Smith criterion was shown to be equivalent to the Frequency Domain Neal-Smith criterion in the analysis of two reliable flying qualities data bases. Its advantage rests in the fact that nonlinearities are readily accommodated. A PIO metric was formed from the Time Domain Neal-Smith criterion by using the time domain task bandwidth parameter as the PIO forcing function and "measuring" PIO tendencies by the sensitivity of the pilot-vehicle closed-loop system response to this input. The PIO forcing function mimics actual "trigger events" and the model outputs represent the configuration flying qualities (pilot compensation and closed-loop stability or oscillatory tendencies) in response to these triggers.

The Time Domain Neal-Smith criterion was also demonstrated in the evaluation of the effects of actuator rate limiting on pitch flying qualities. Because of its time domain formulation, assumptions of linearity or a priori assumptions of the nature of pilot control inputs/activity for describing function analyses were not necessary. The PIO-causing effects of rate limiting were clearly identified using this technique.

A proposed quantitative PIO metric was evolved from the Time Domain Neal-Smith criterion. This metric was shown to be quite successful in identifying the PIO tendencies of the configurations from the LAHOS and Neal-Smith data bases.

A. <u>Plan for Follow-On Work</u>

The basic criterion is currently limited to the analysis of pitch control only. It is assumed that satisfactory pitch control is always a necessary but for some tasks perhaps not sufficient prerequisite for good longitudinal flying qualities. Work was begun to extend the criterion to include the effects of flight path control in the evaluation of longitudinal flying qualities and PIO tendencies. This work was stopped, however, to meet the first priorities of this effort. This work should be continued and completed.

The Time Domain Neal-Smith concept should also be extended to roll control. The time domain aspects of such a criterion should be advantageous in the analysis of actuator rate limiting deficiencies during roll control. The Frequency Domain Neal-Smith criterion has been extended for roll flying qualities evaluations so a precedence is available.

The software which is used to compute the Time Domain Neal-Smith criterion should be revised so that the configuration maps are readily produced to support the PIO metric analysis. The current maps were generated before evolution of the PIO metric and, as a result, the maps were not as smooth or as piece-wise continuous as desired to extract the PIO measures.

Additional work is required in the formulation of the PIO metric itself. The results to date are quite good, but the computations may not be rigorous and the conditions not sufficient. With a revised configuration mapping procedure, the PIO metric will be re-evaluated. The PIO tendencies of a configuration are easily deduced from the configuration maps - this characteristic will not change; the difficulty is in finding reliable, repeatable measures which quantify the qualitative characteristics. In general, a good measure has been found but it needs additional testing for robustness and repeatability. Also, the task bandwidth for which a configuration "exceeds" the PIO threshold may be an important PIO/flying qualities measure. This fact was demonstrated with the rate-limited actuator evaluations but insufficient data were available to support a numerical requirement.

Finally, mission relevance should be "applied" to the criterion and its closed-loop tracking task. The agility work conducted by the USAF should be incorporated into the Time Domain Neal-Smith criterion for the selection of the step target command sizes, required acquisition times, and allowable pipper errors. For example, a parameter such as D representing task aggressiveness should be related to specific mission tasks much as bandwidth in the Frequency Domain Neal-Smith was. This correlation will tie the PIO/flying qualities analysis to actual aircraft missions, mission task-elements and aircraft performance requirements – including pilot controllability, within the context of the agility metric development work and of the proposed criterion. The Time Domain Neal-Smith criterion can then be used to bridge the complete development cycle of an aircraft design - from paper design to meet mission requirements and establish control law requirements through to operational flight testing and evaluation. Pilot-in-the-loop simulation and actual vehicle flight testing should be used to validate that these mission relevant parameters have been successfully incorporated into the flying qualities/PIO criterion.

Section 6.0
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Appendix A
Bibliography of PIO Data/Research

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Appendix B
New/Hard-to-Find PIO Data

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Appendix C
Pilot Model Software User's Guide

A user's guide is not available at this time. However, an outline of the software used to compute the Time Domain Neal-Smith criterion is given.

The software which is used to develop the criterion measures was coded in Fortran using continuous simulation of the augmented aircraft and pilot compensator.

A Rosenbrock constrained optimization algorithm (Reference 26) was used to optimize the closed-loop simulation. The algorithm followed the flow chart of Figure C-1.

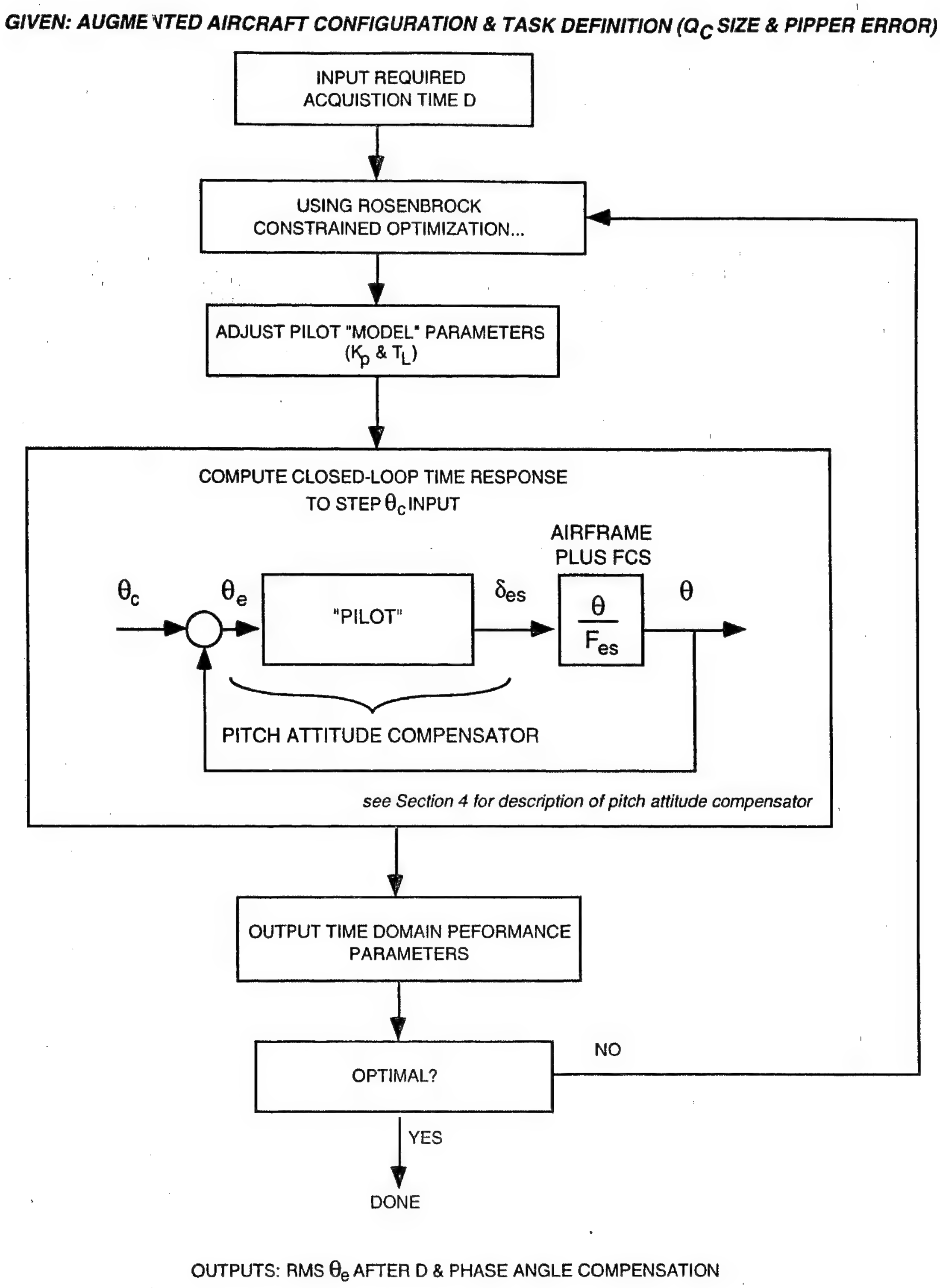
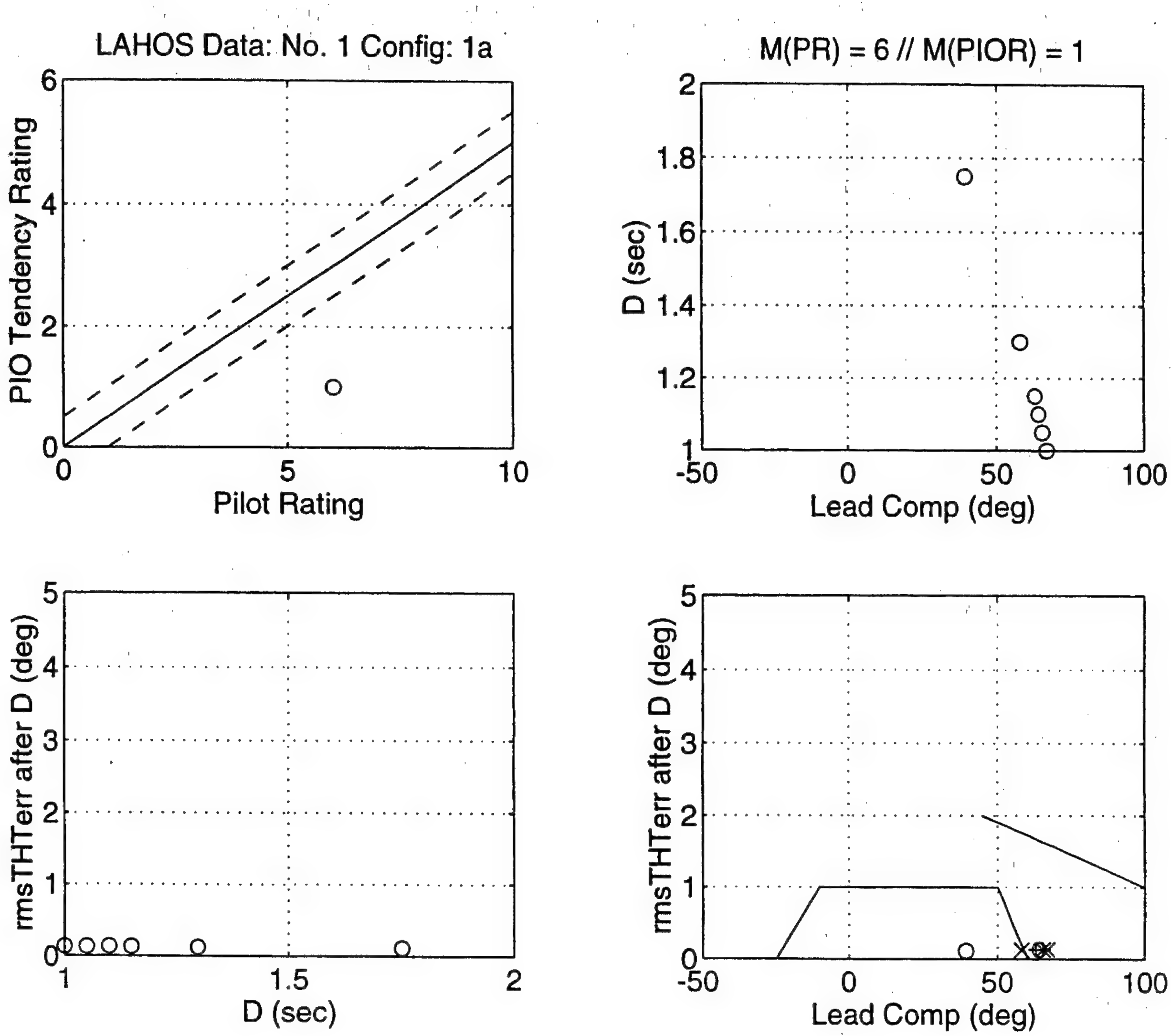


Figure C-1: Flow Chart for Time Domain Neal-Smith Criterion Model

Appendix D
Configuration Mappings



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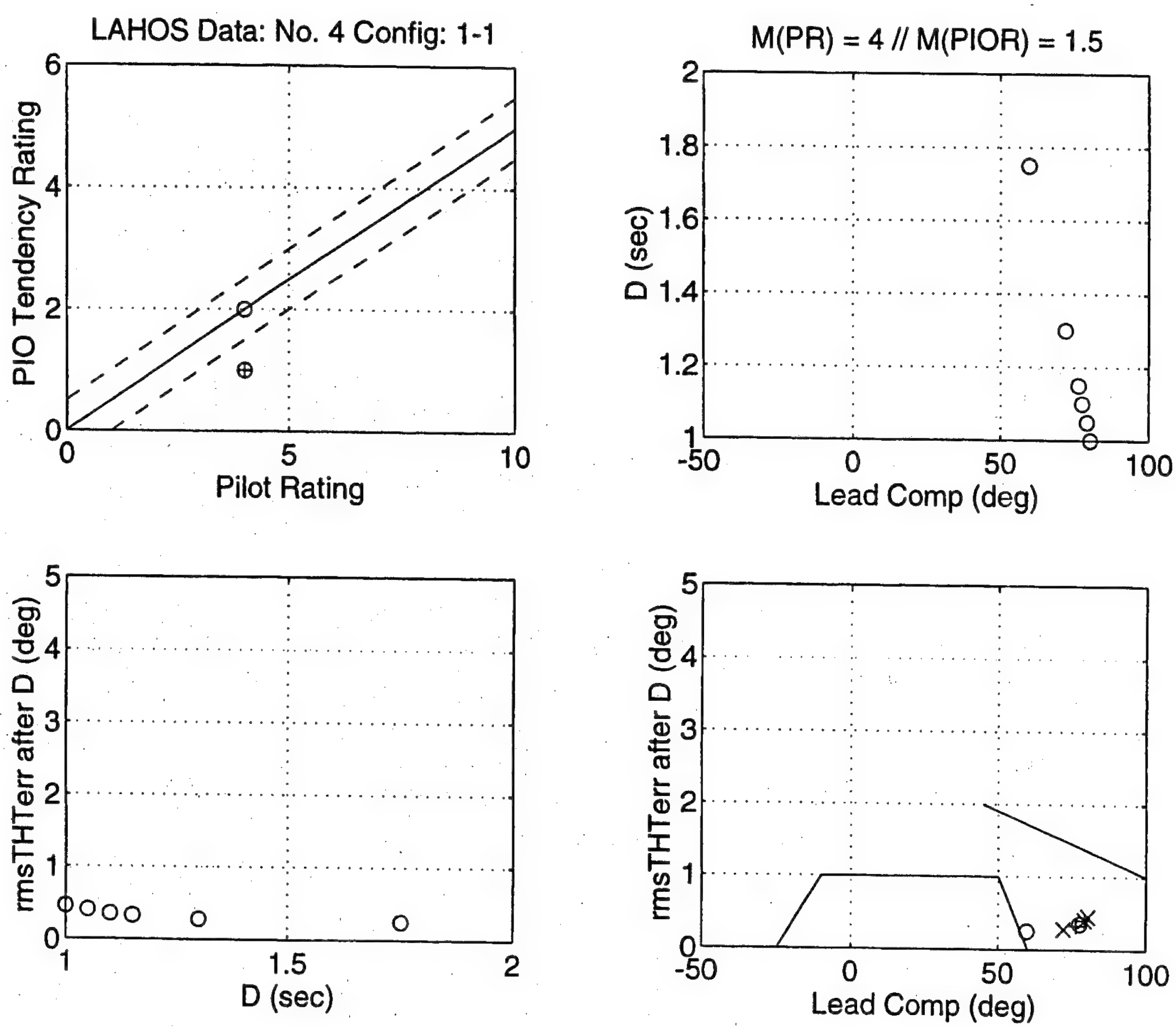
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)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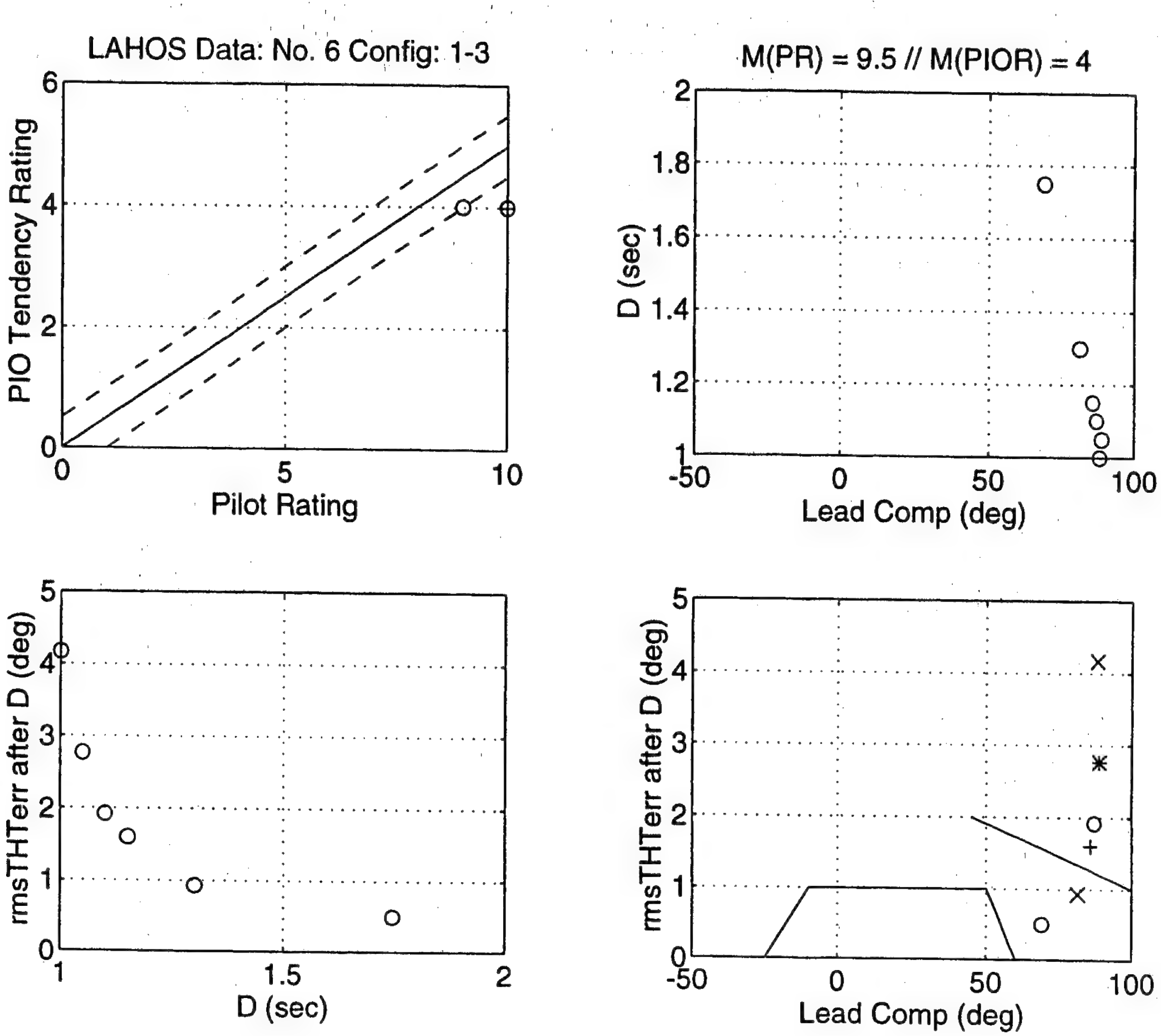

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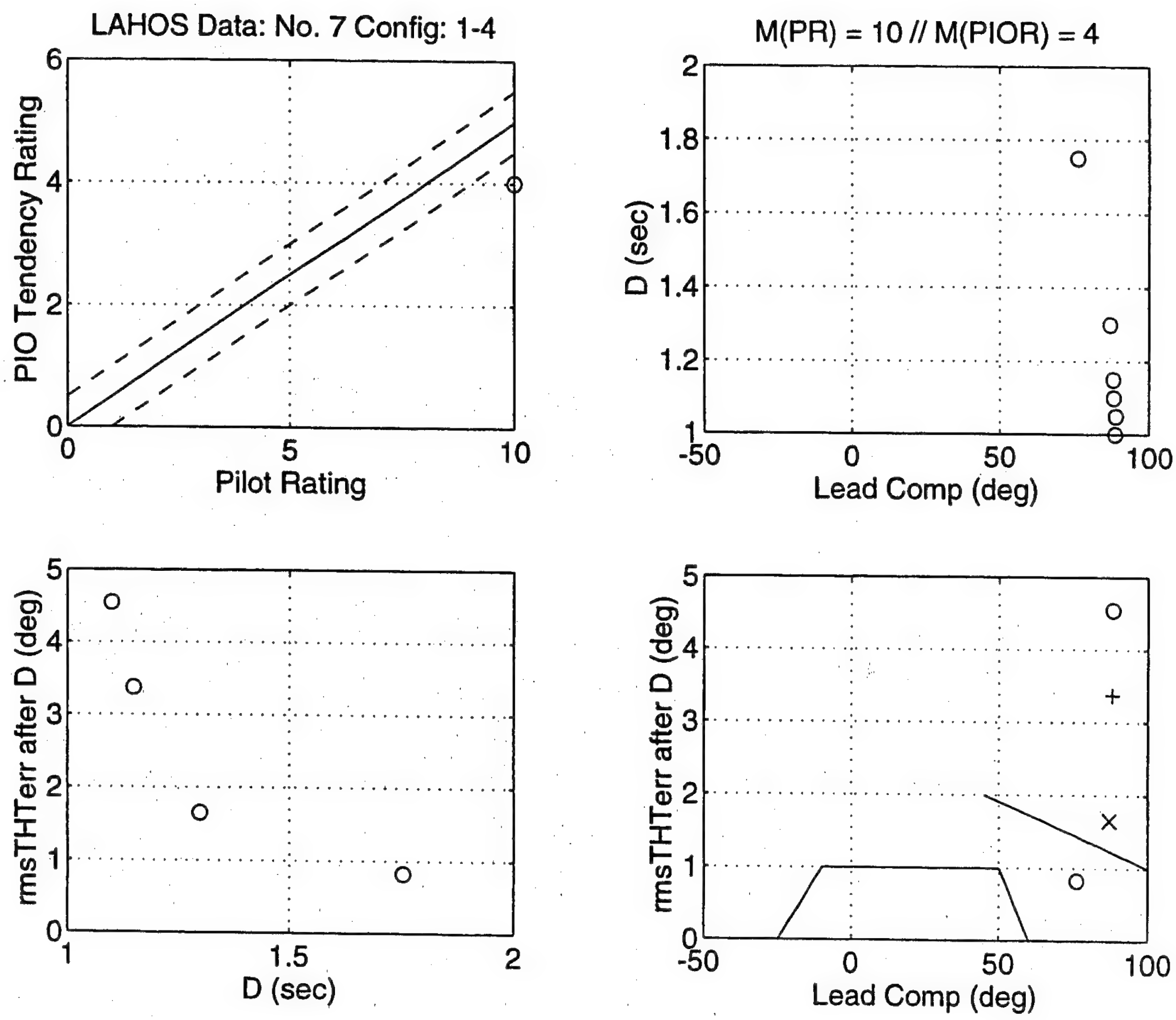
Lead Comp (deg)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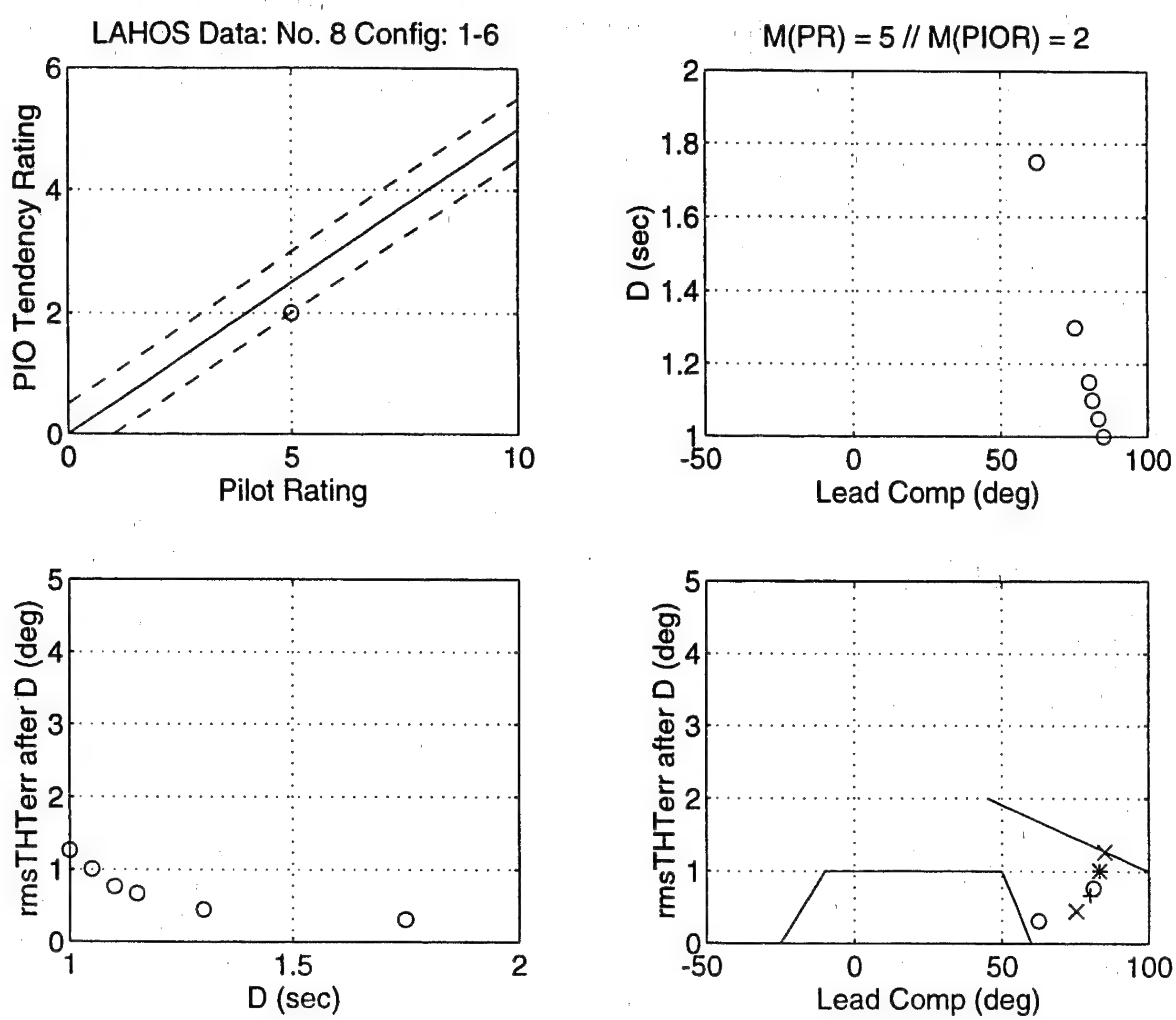
Lead Comp (deg)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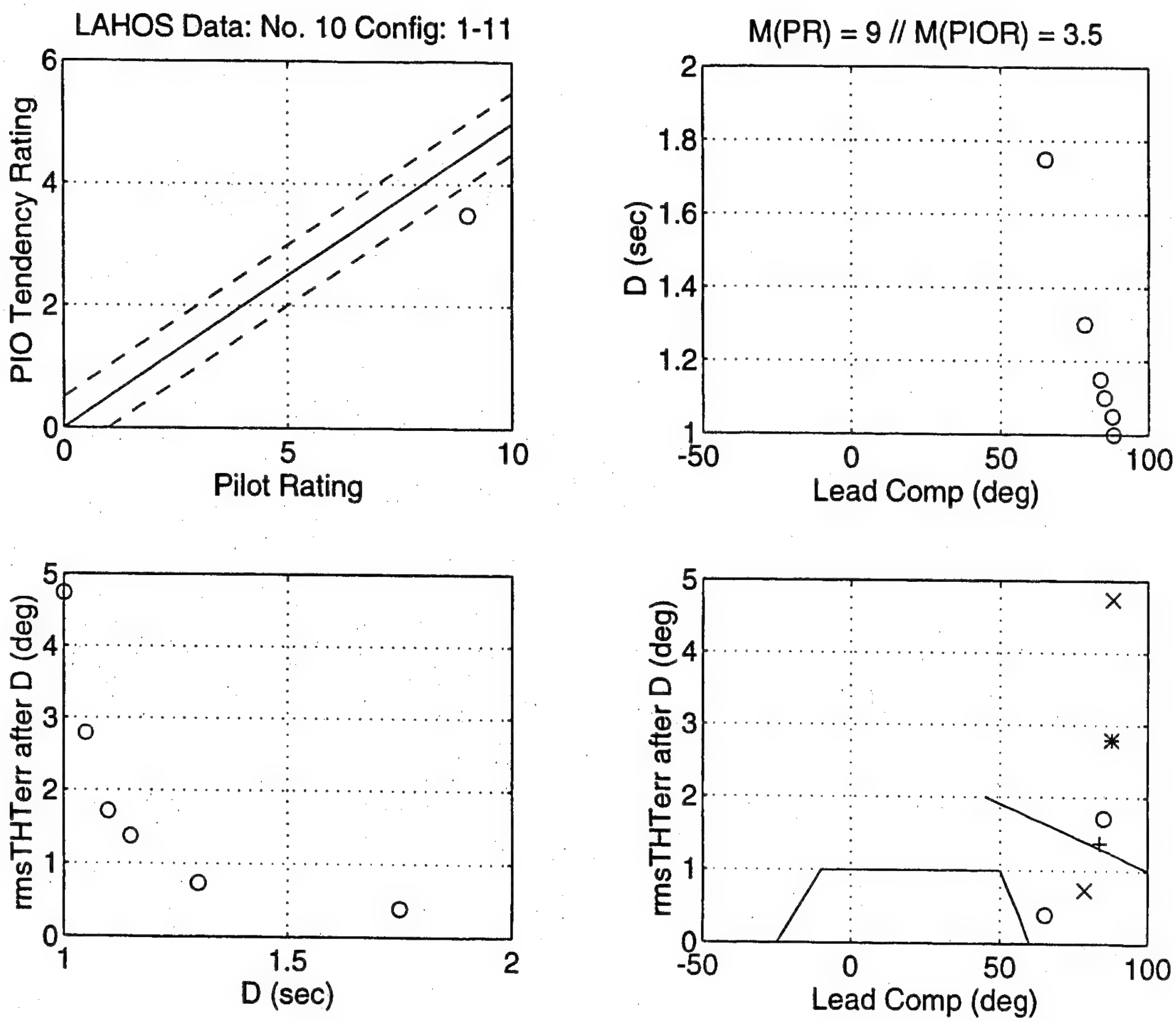
Lead Comp (deg)



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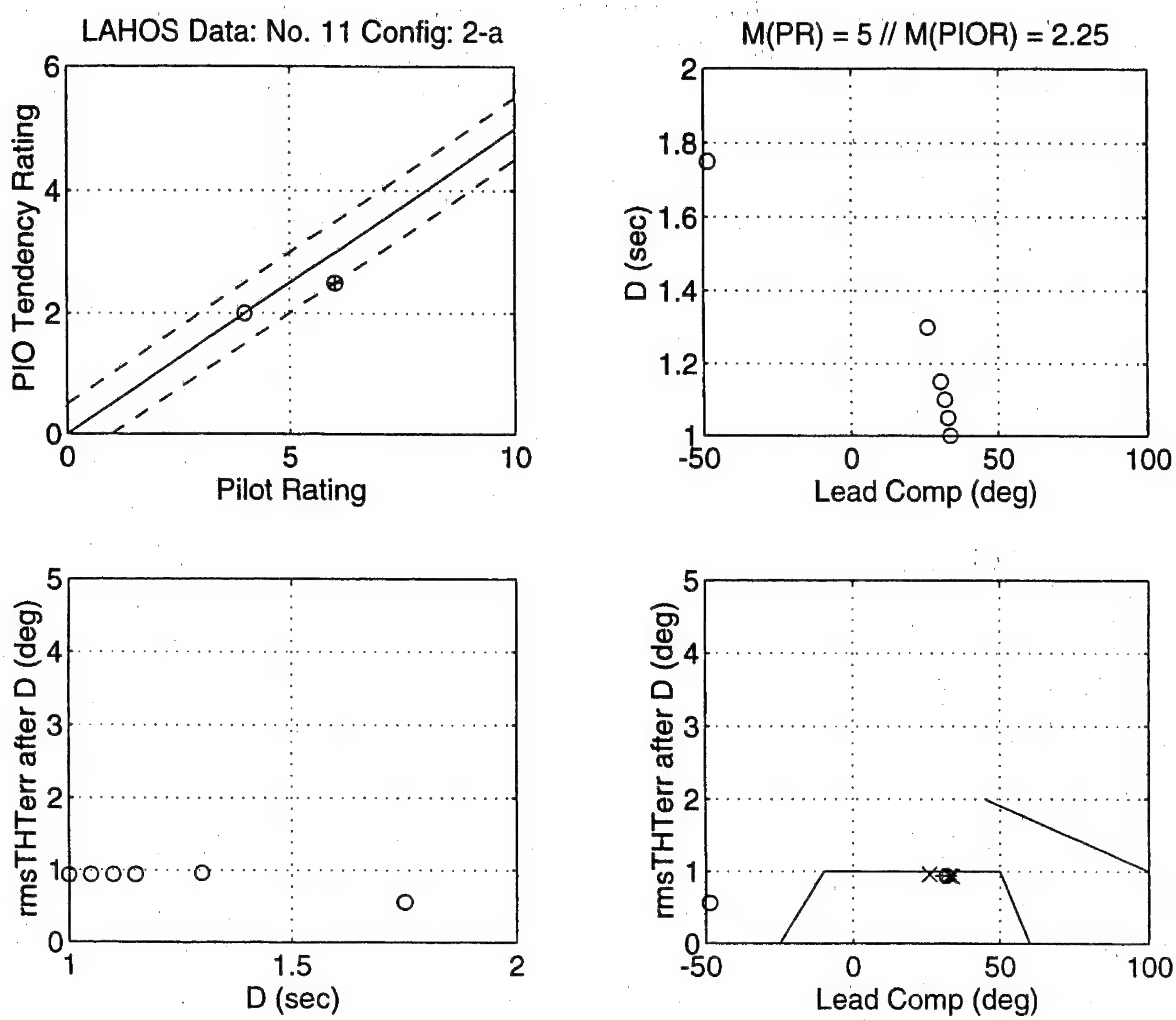
Lead Comp (deg)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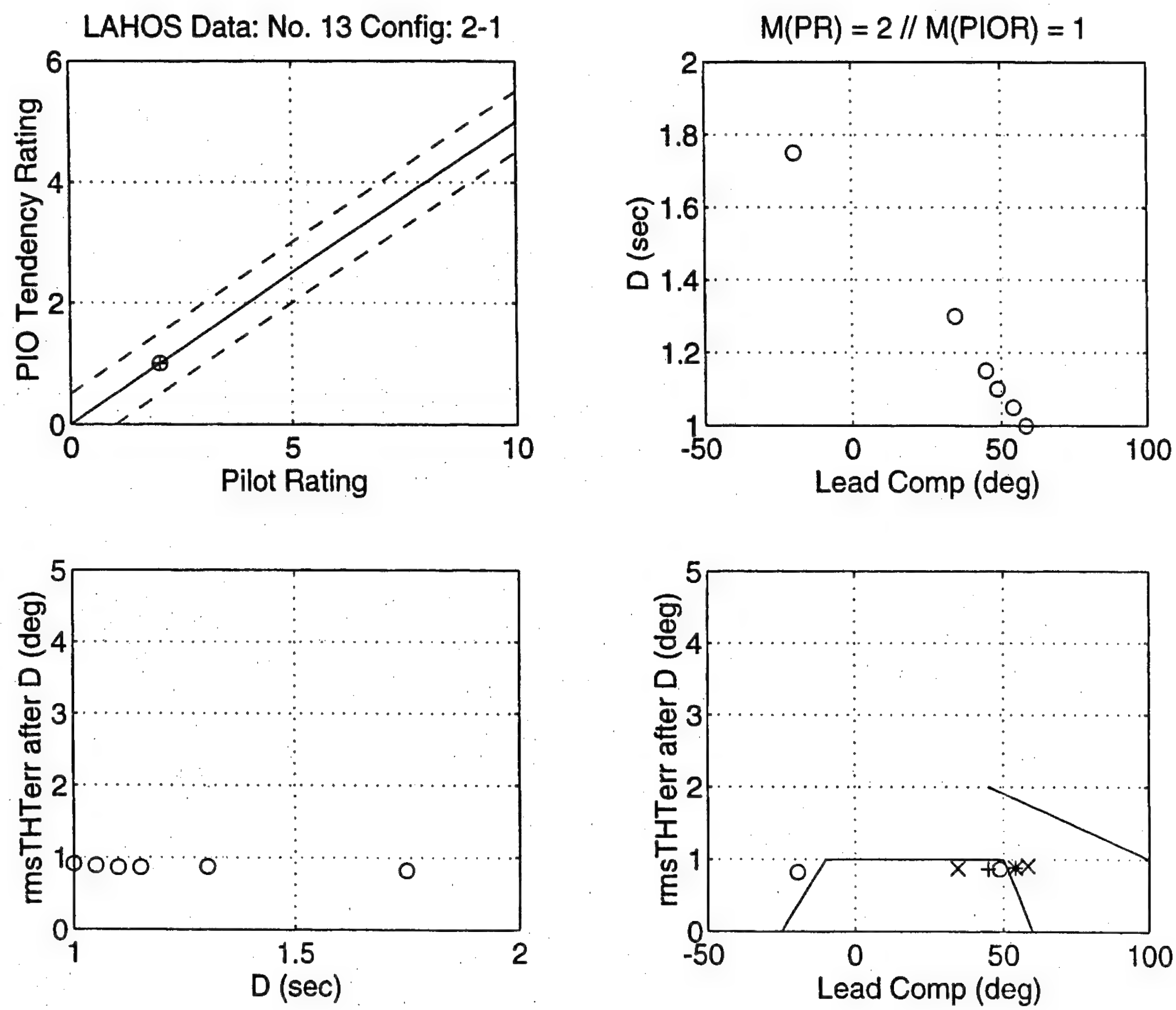
Lead Comp (deg)



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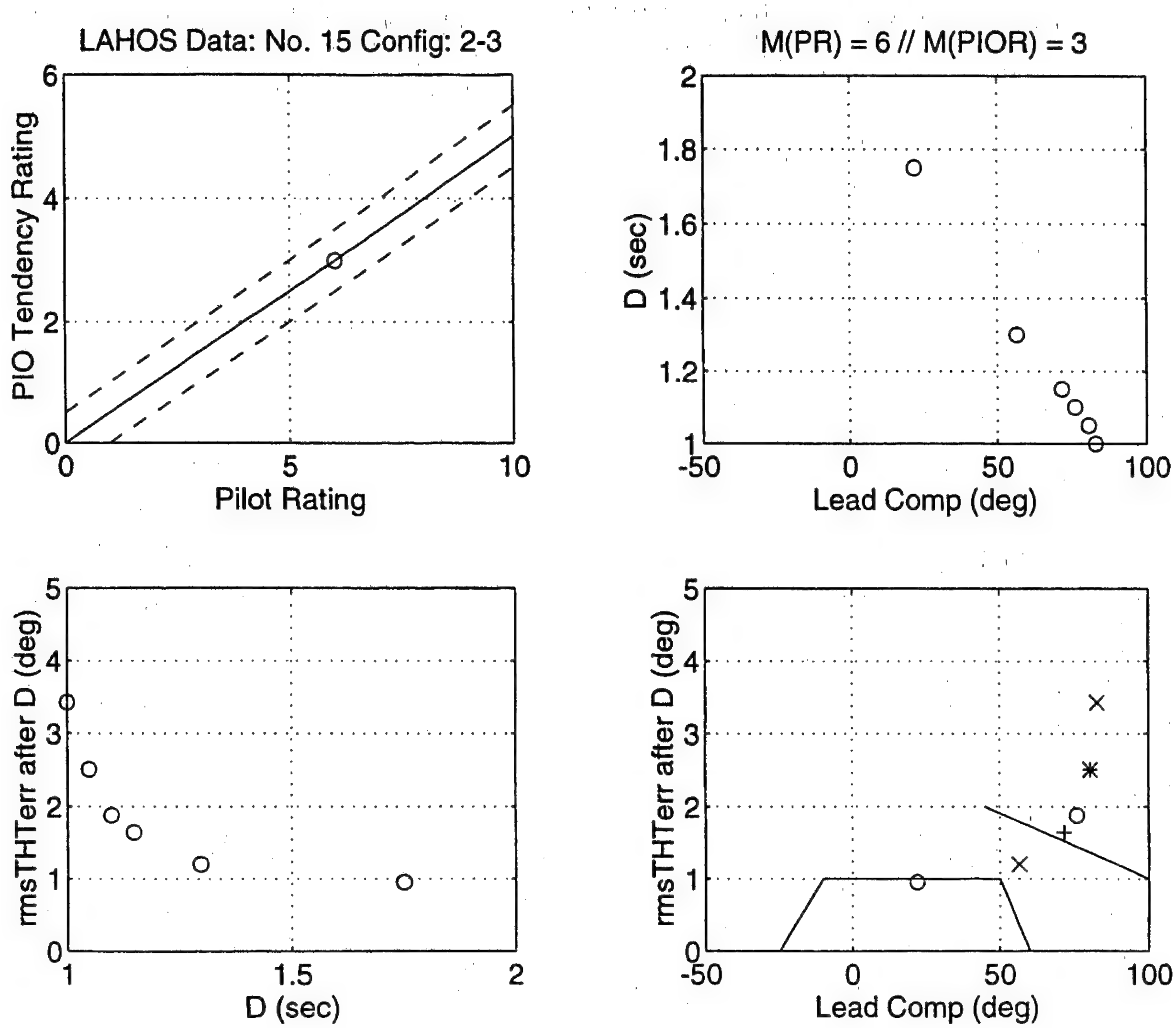

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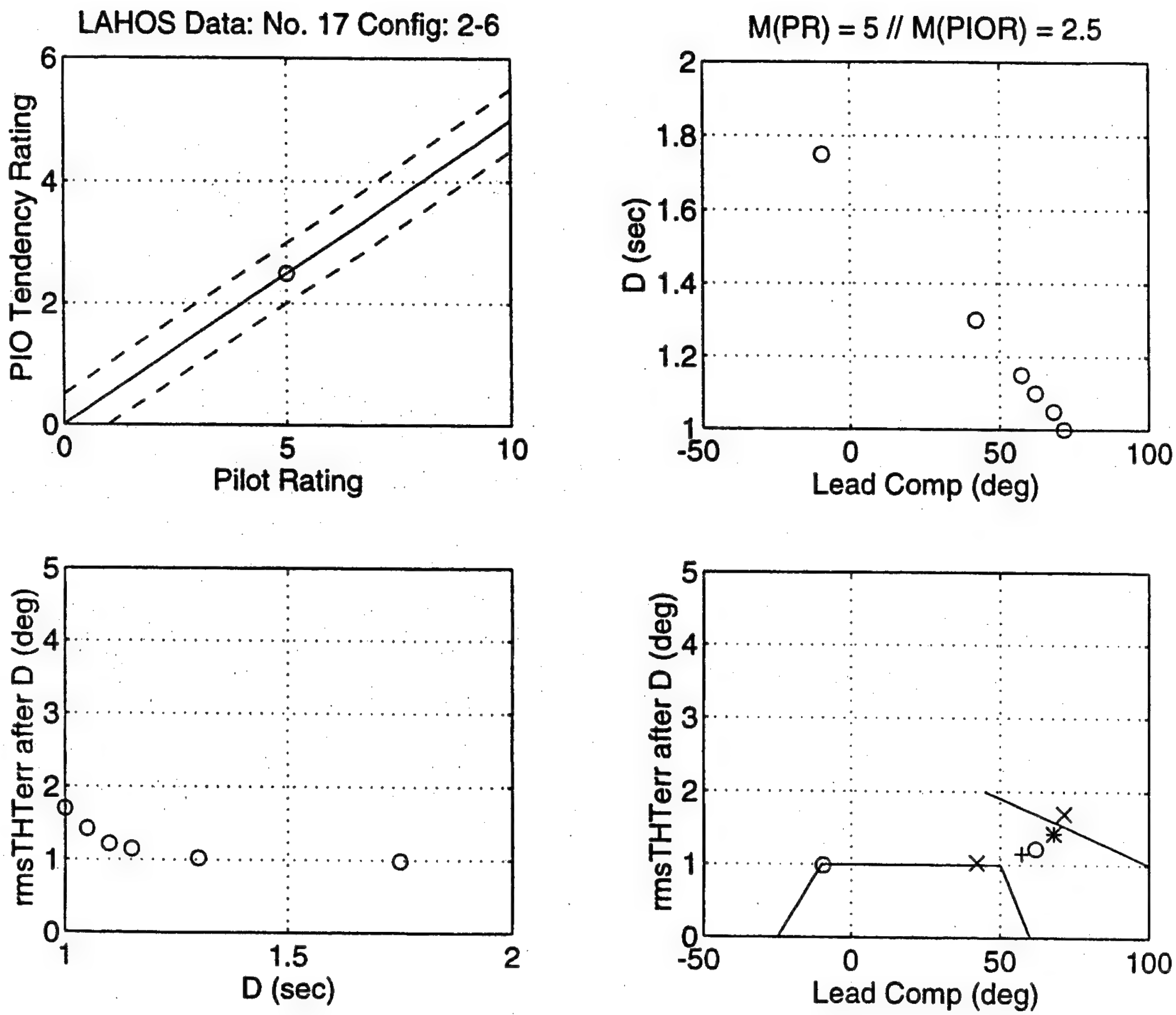

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2
3
4
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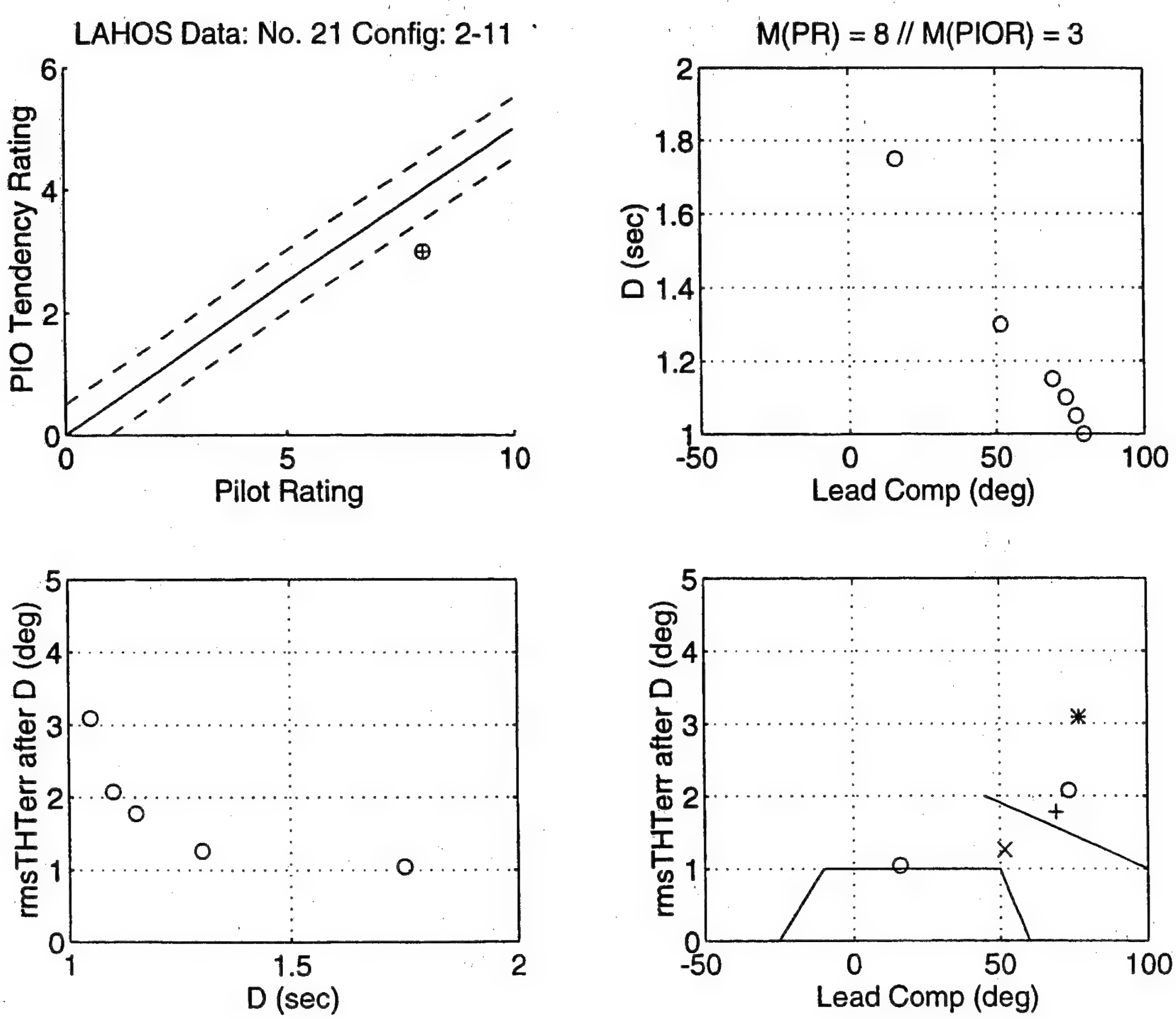

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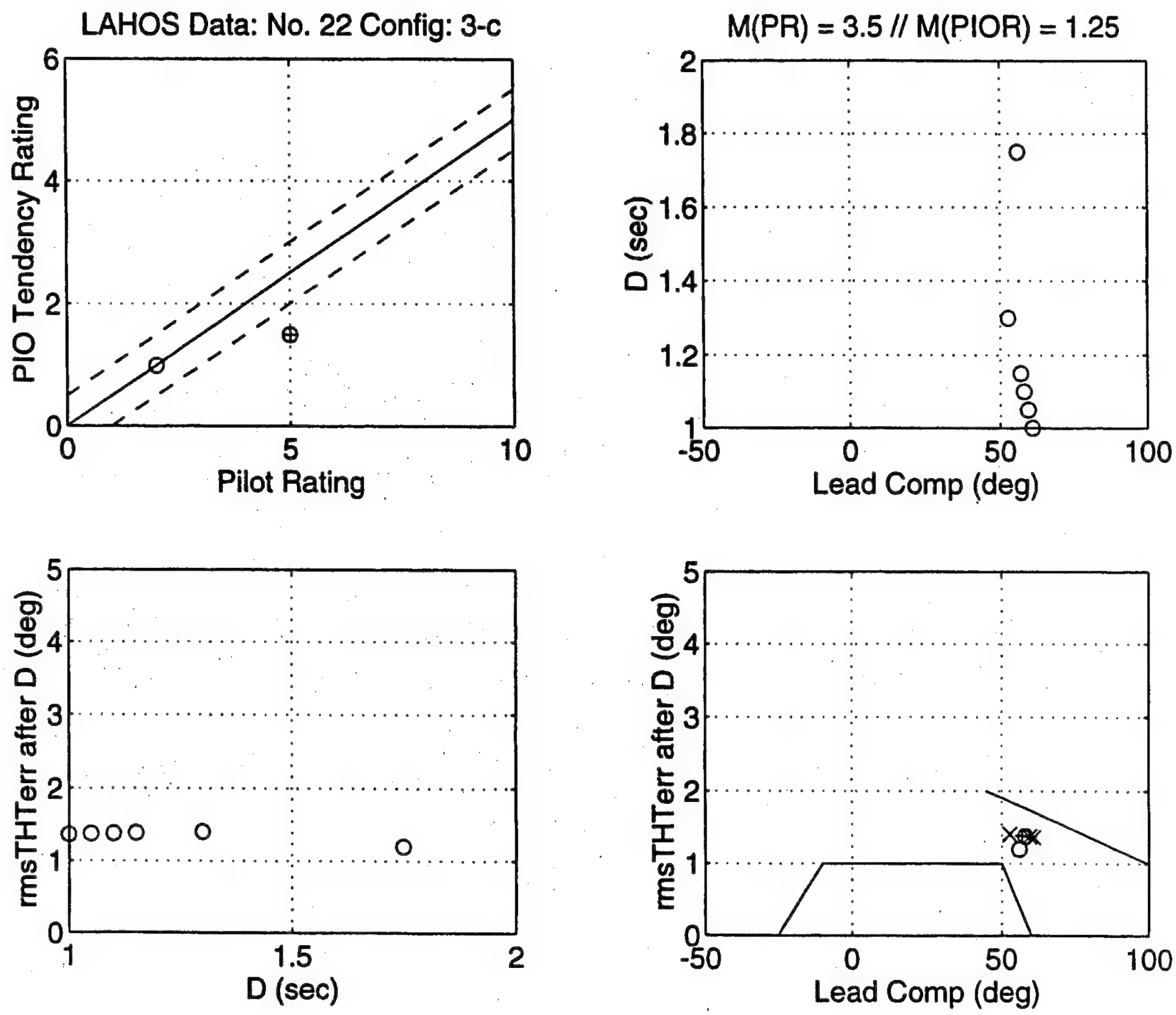
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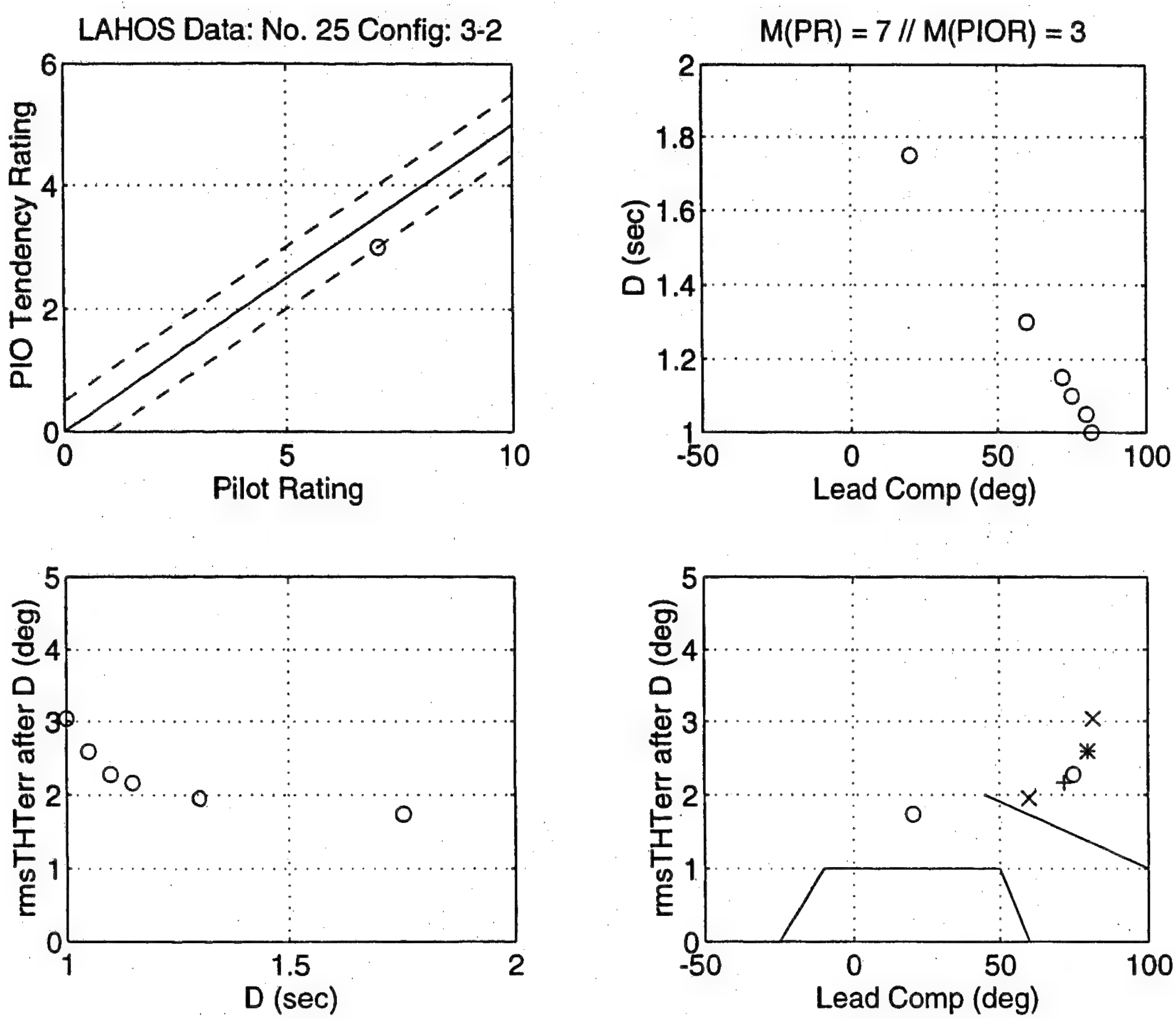

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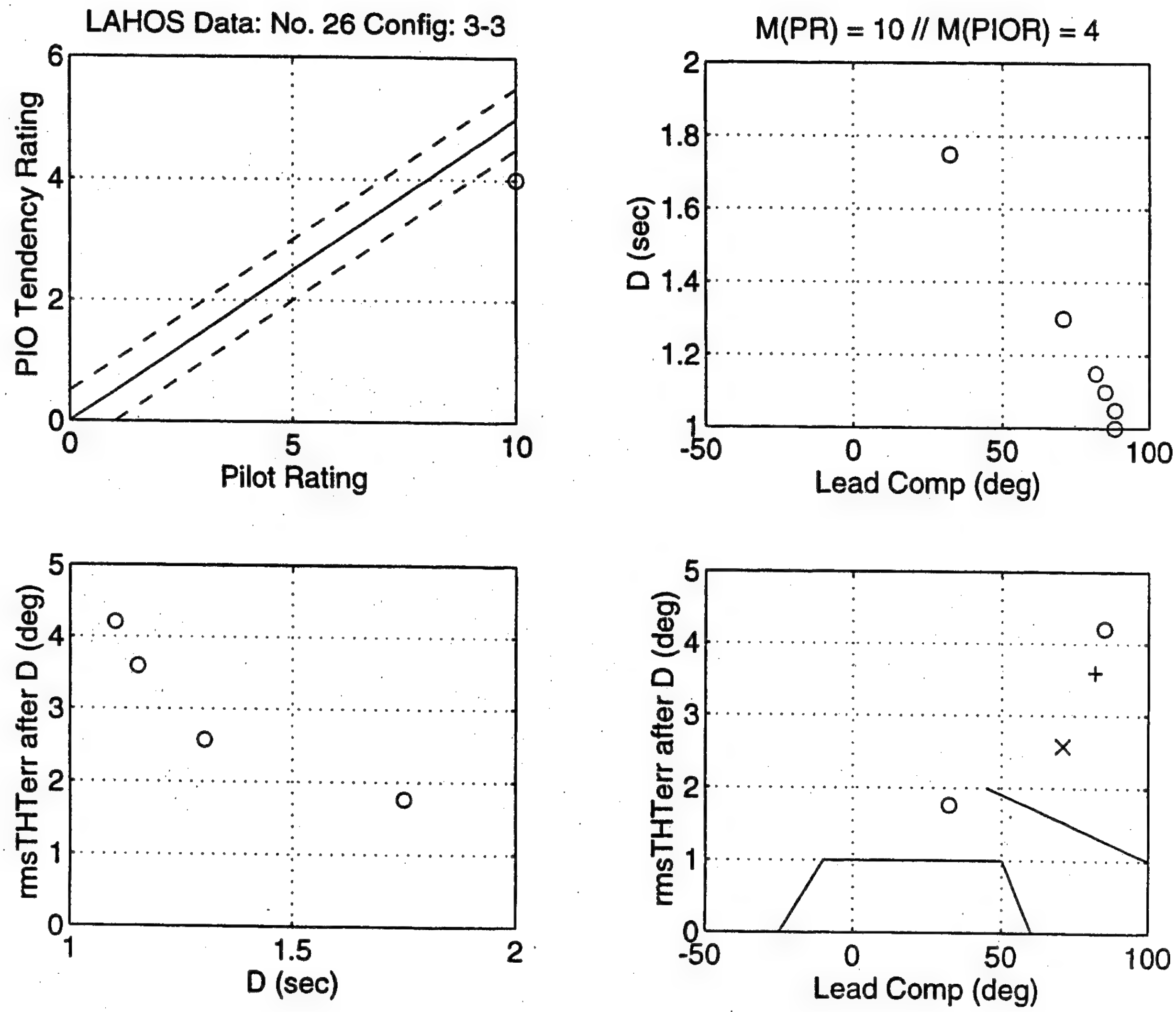

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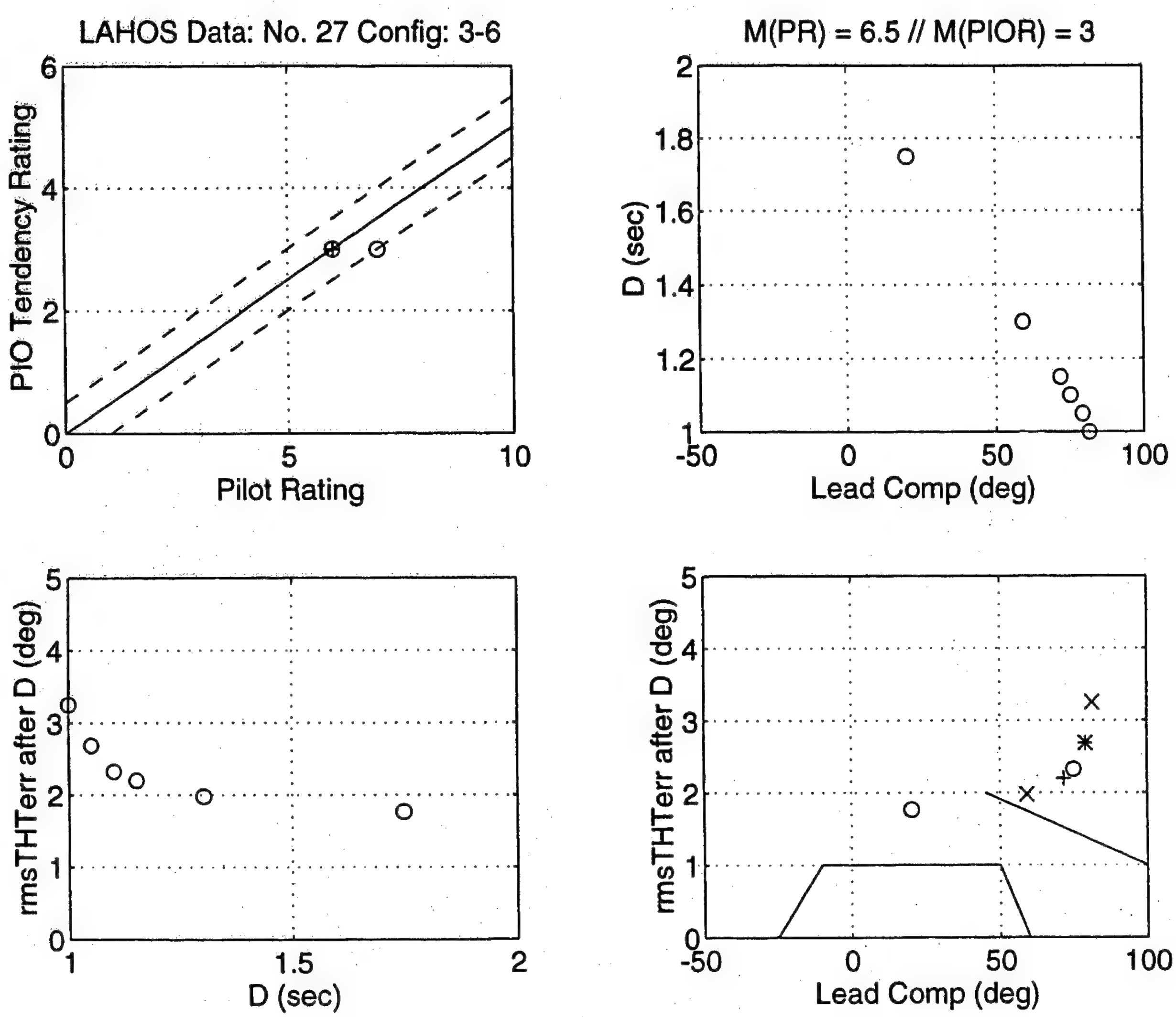

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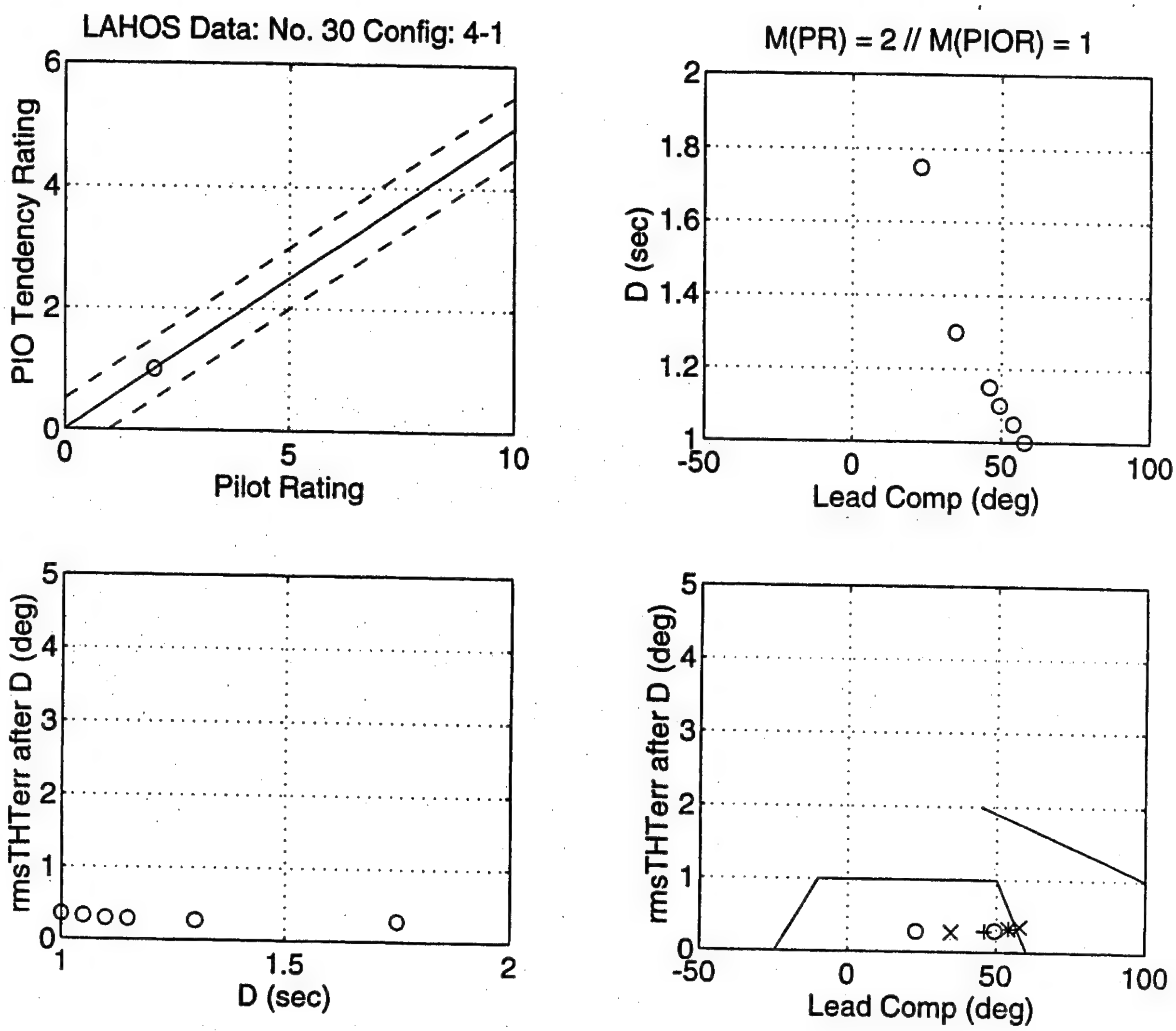
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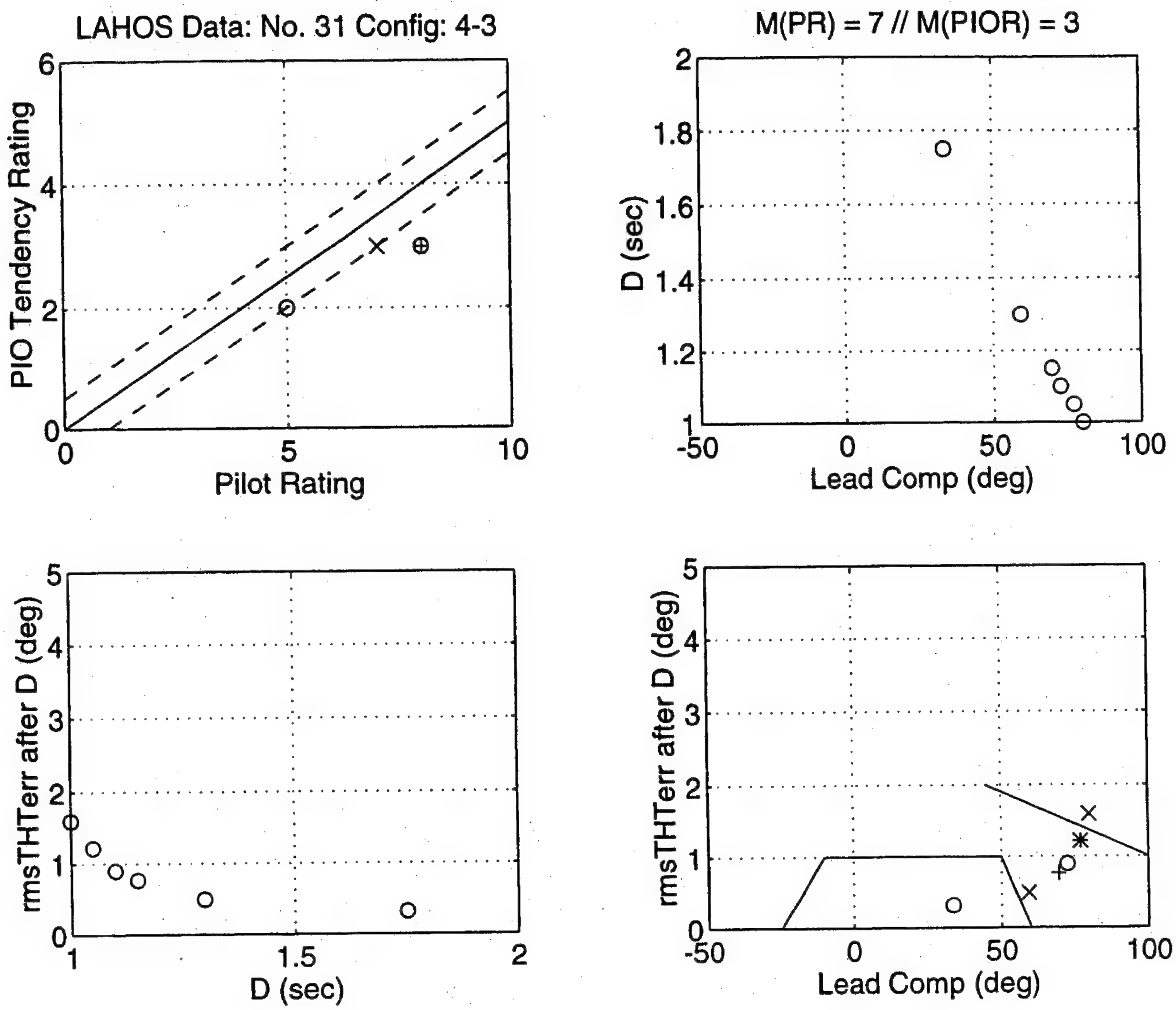
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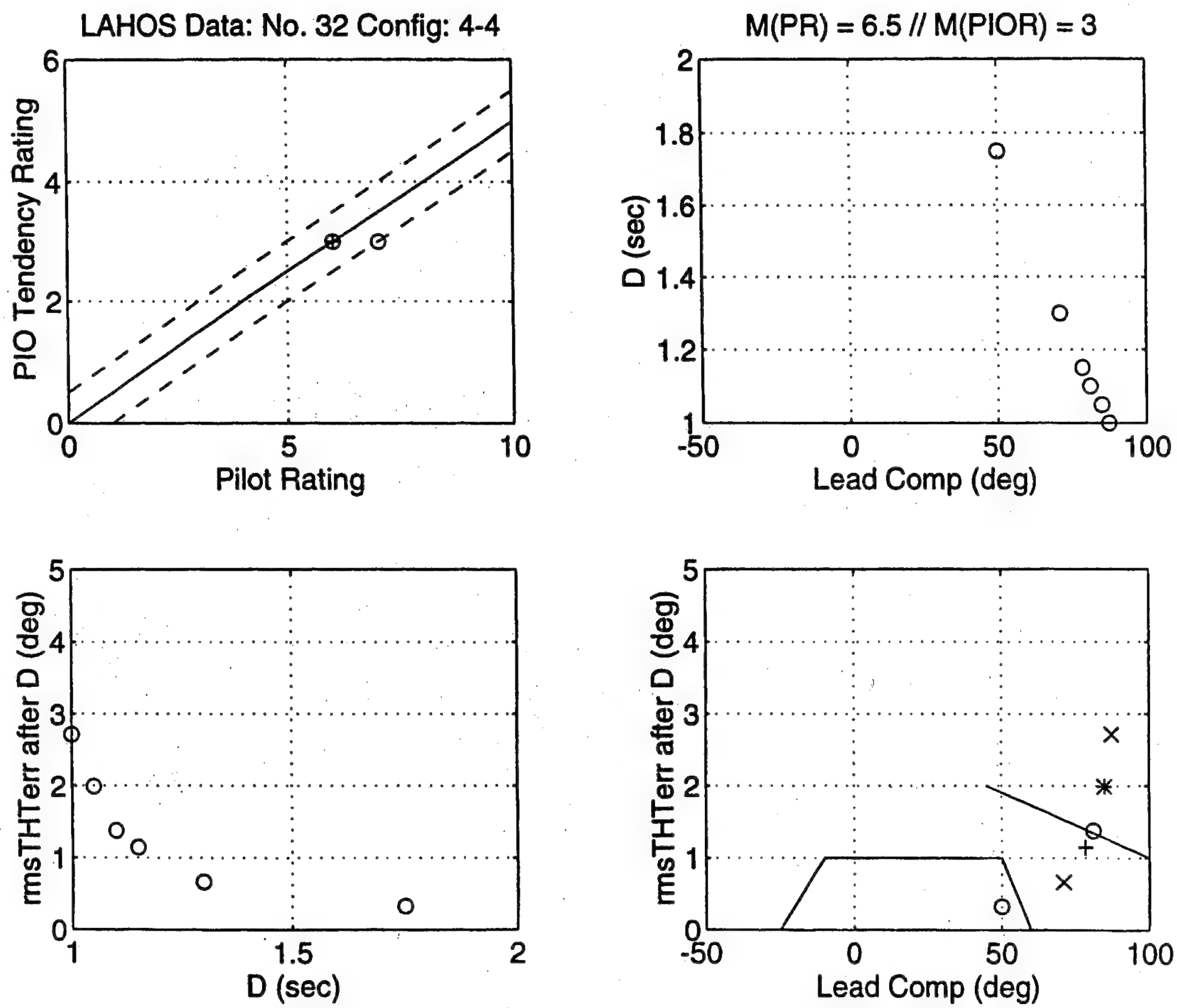

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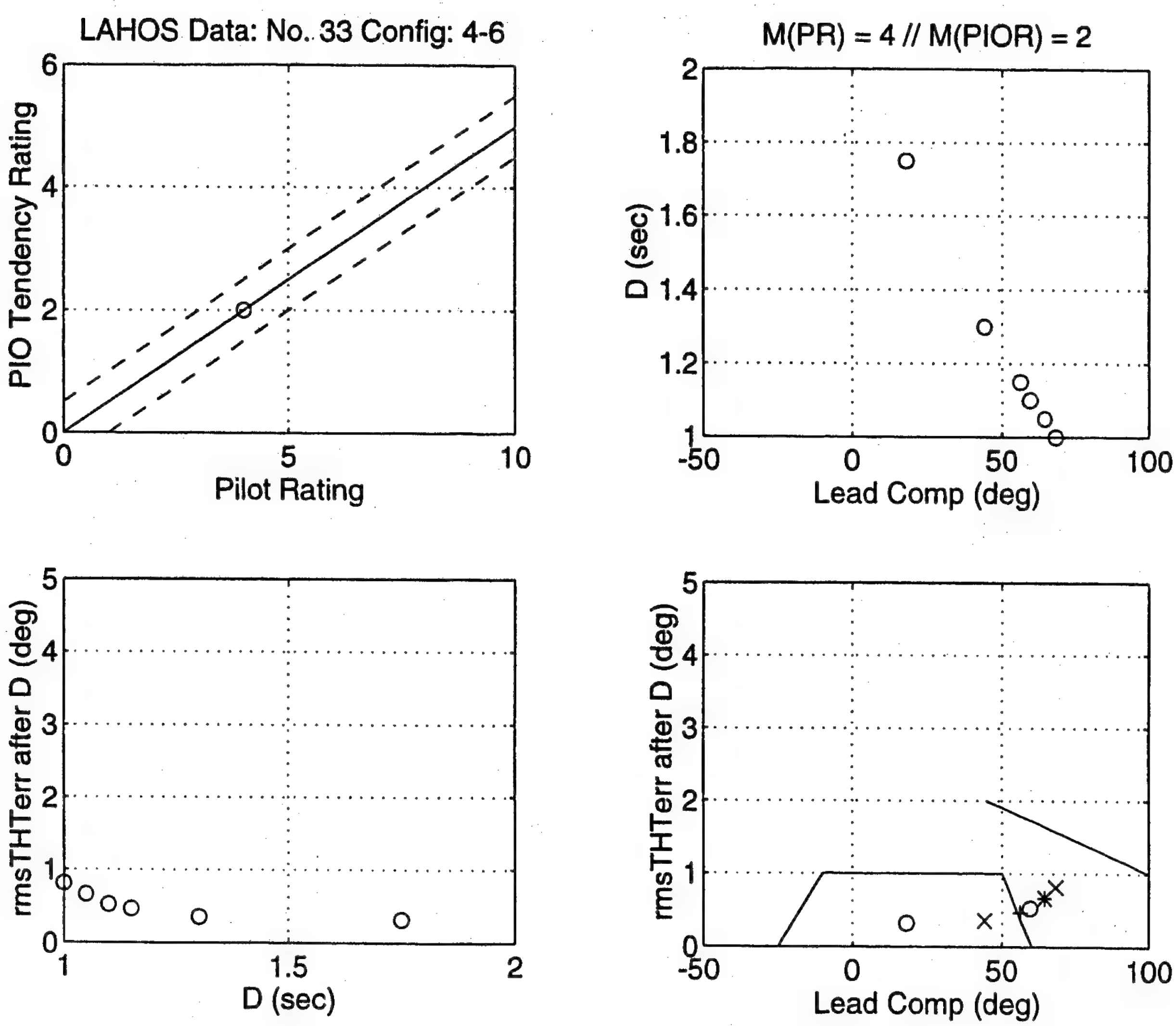
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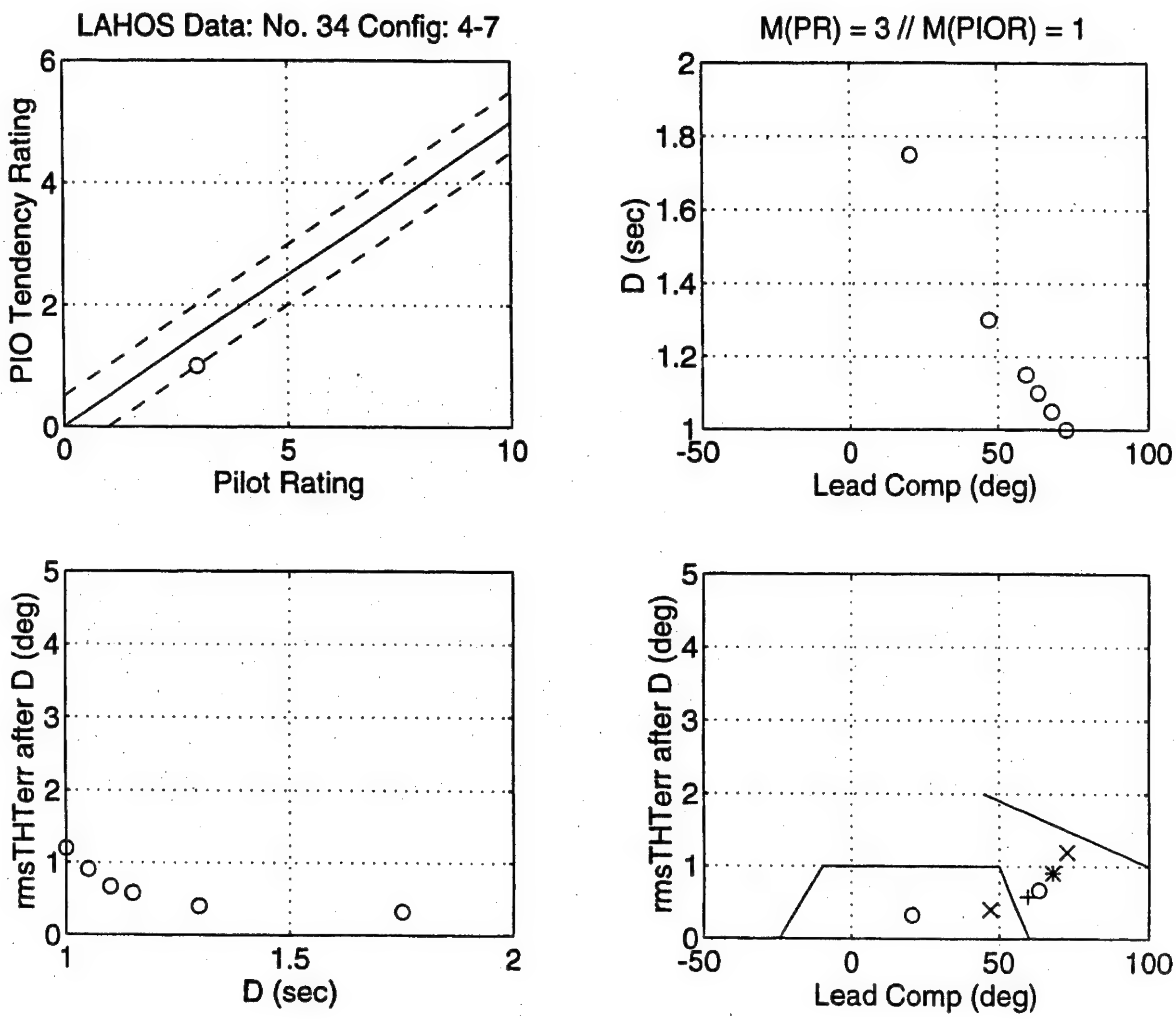

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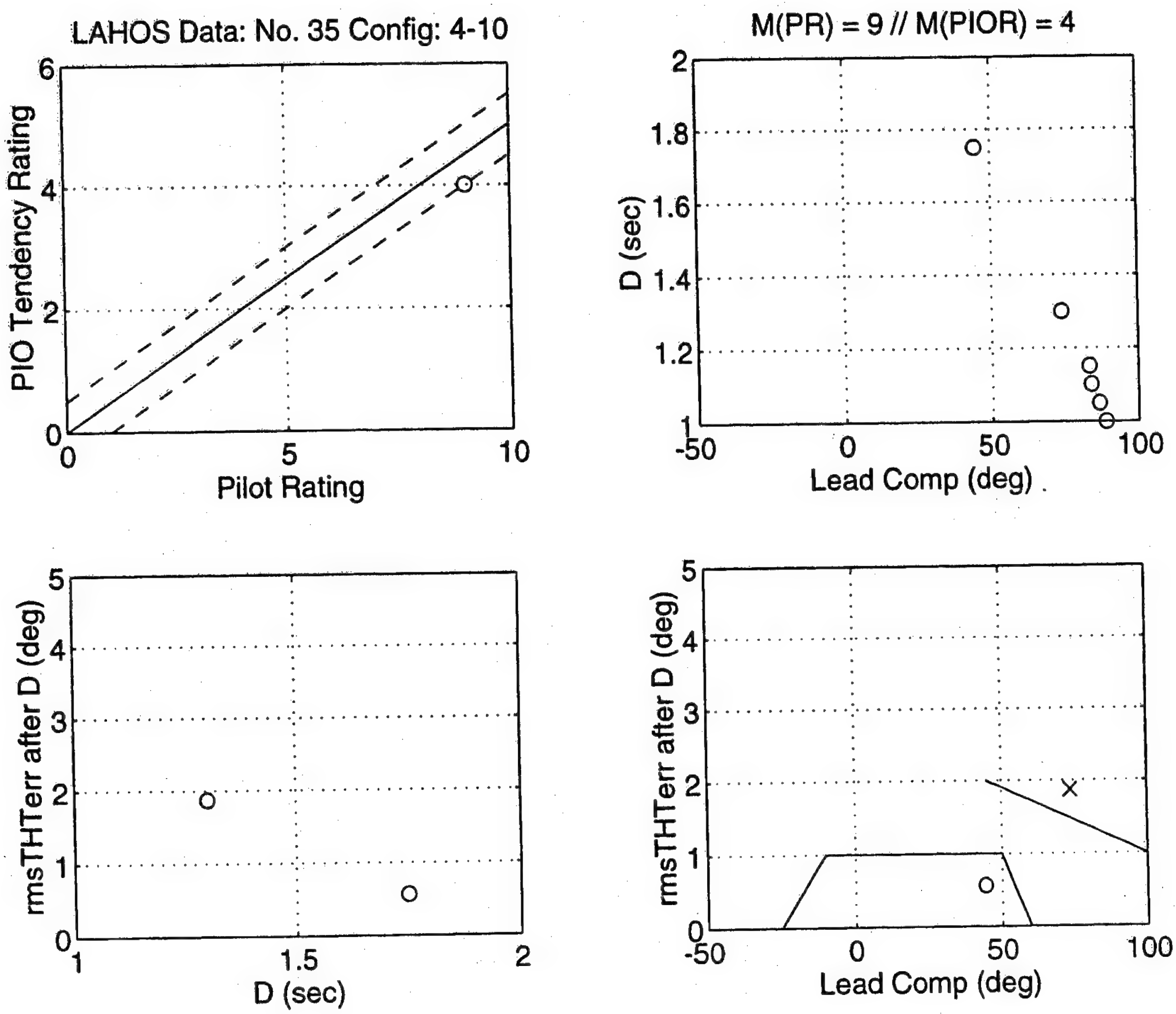
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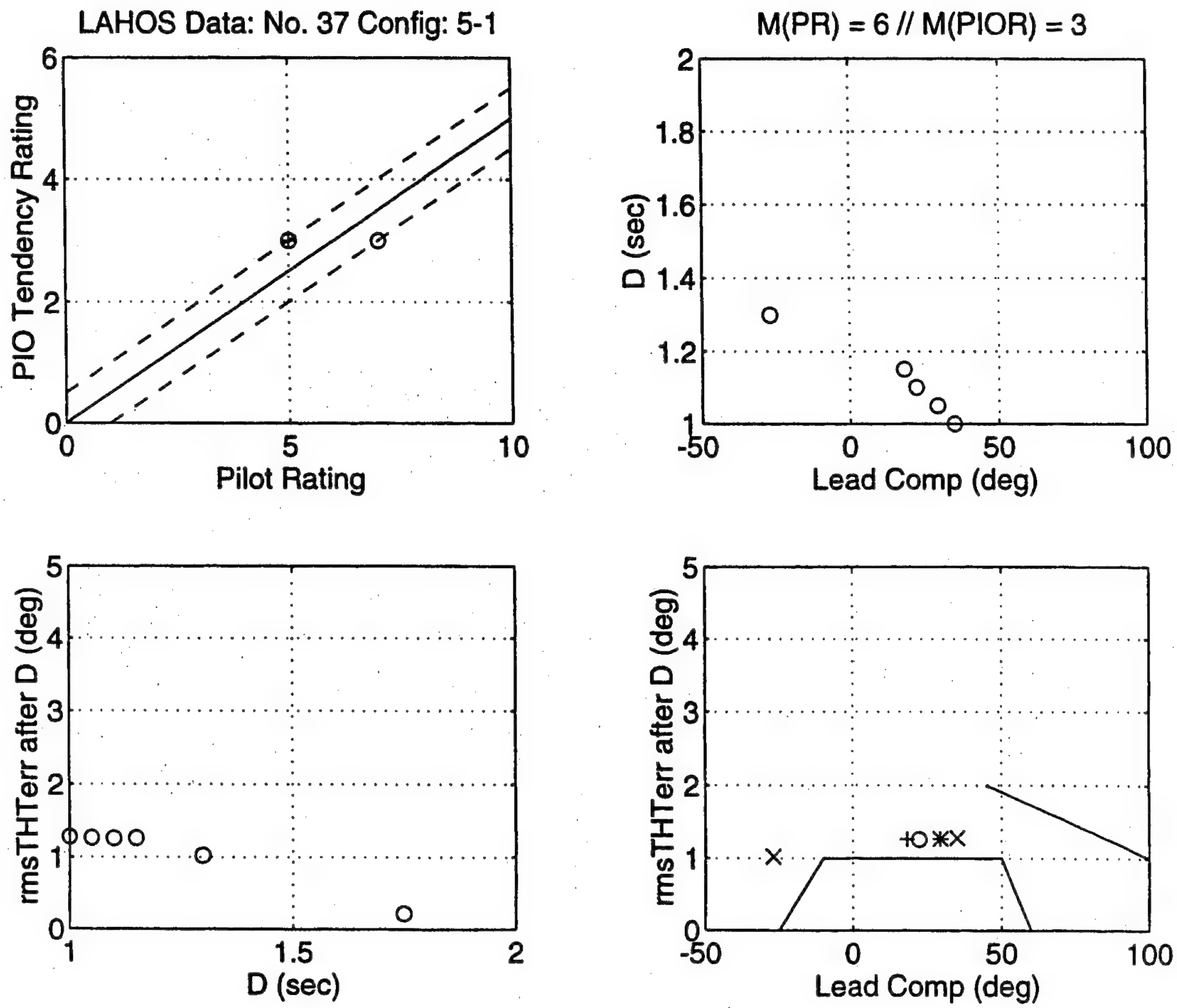

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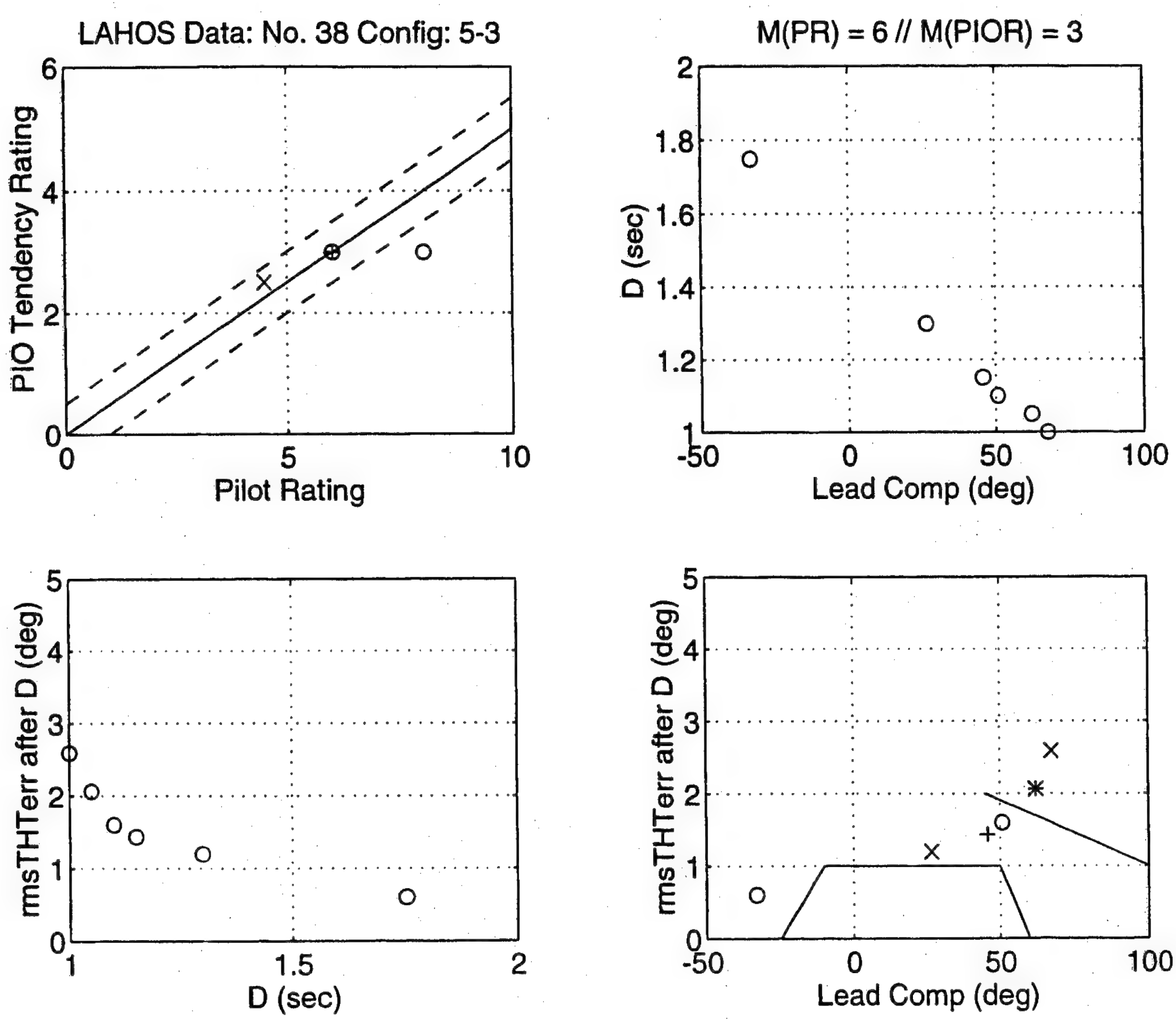

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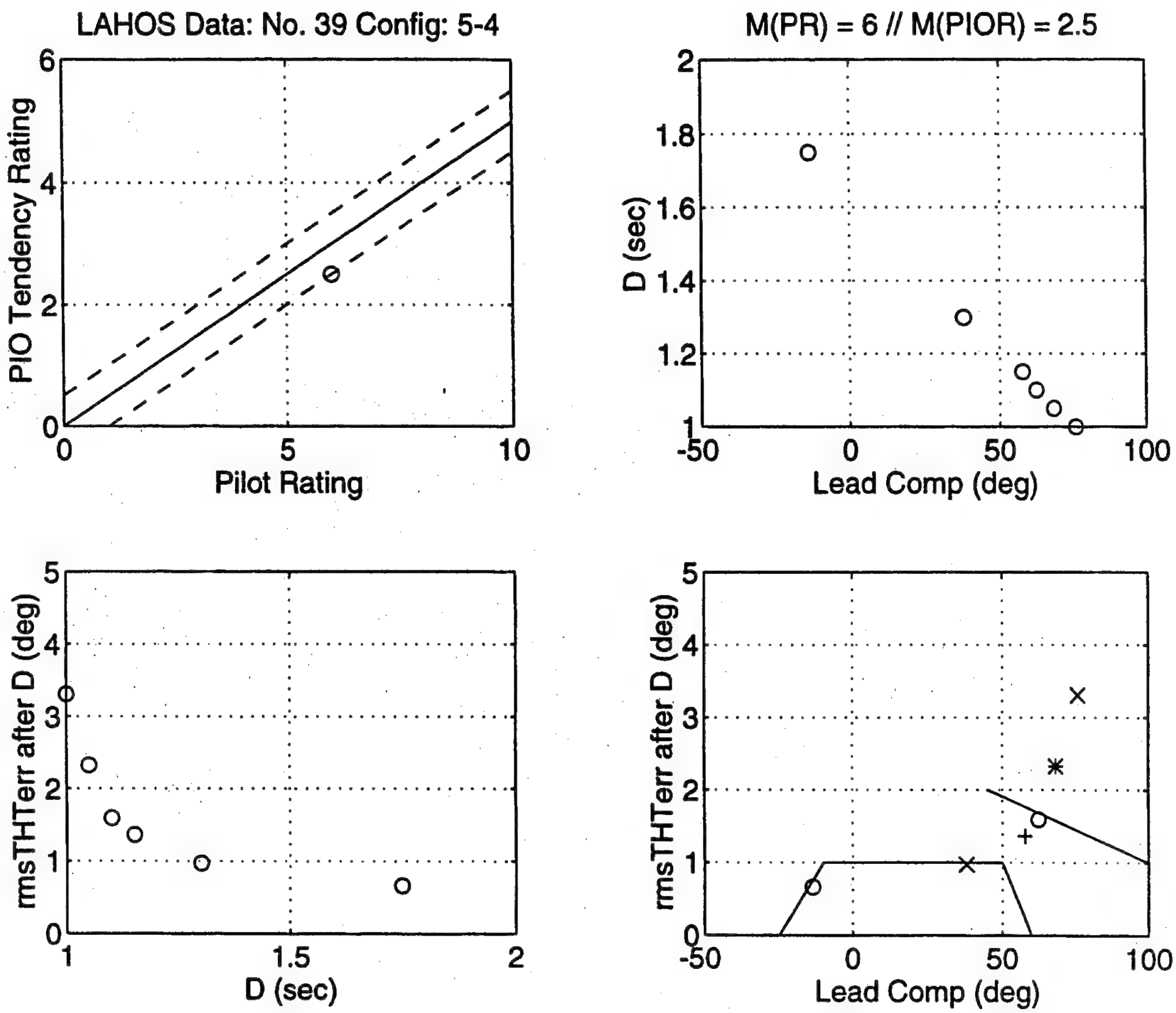
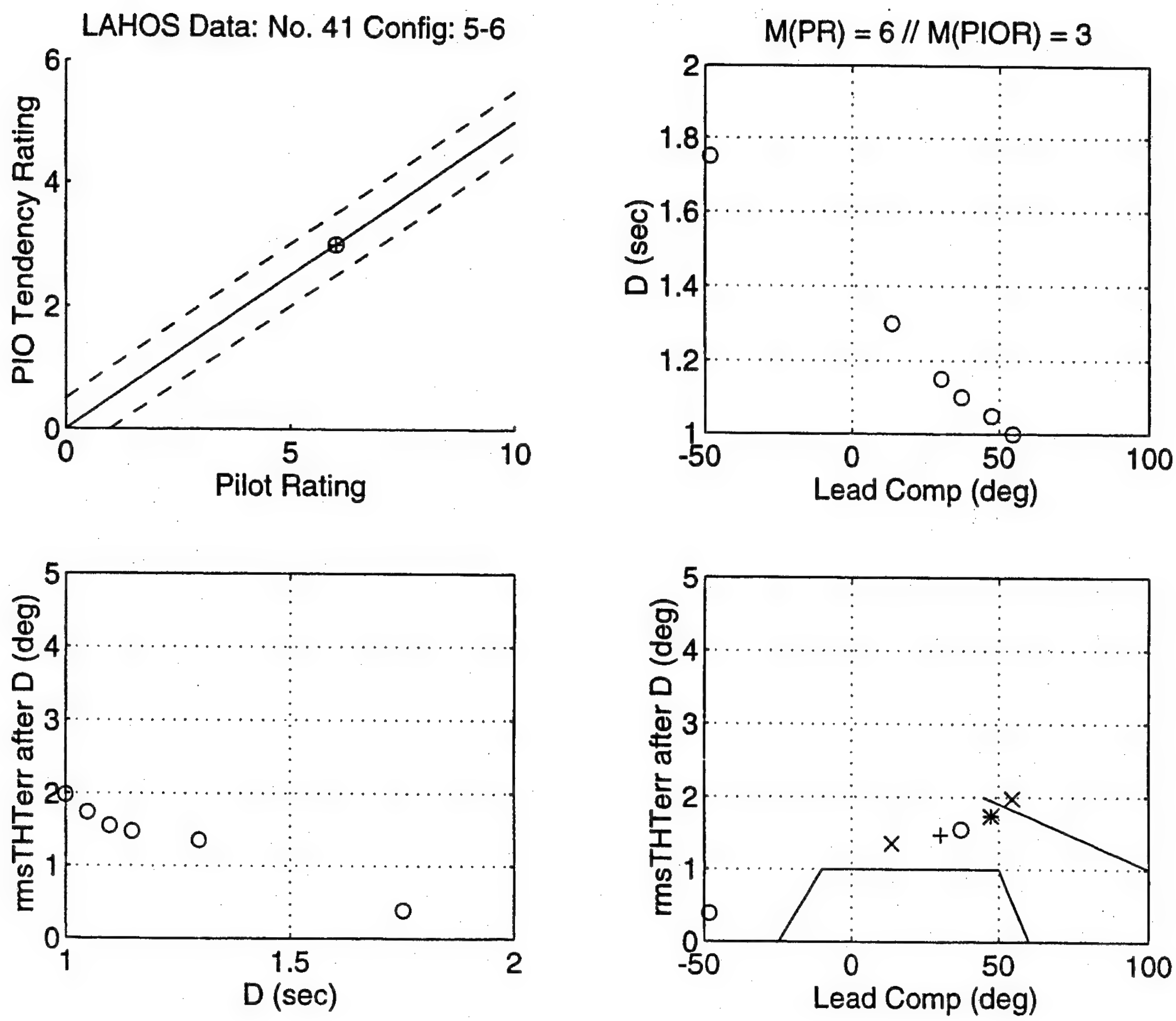
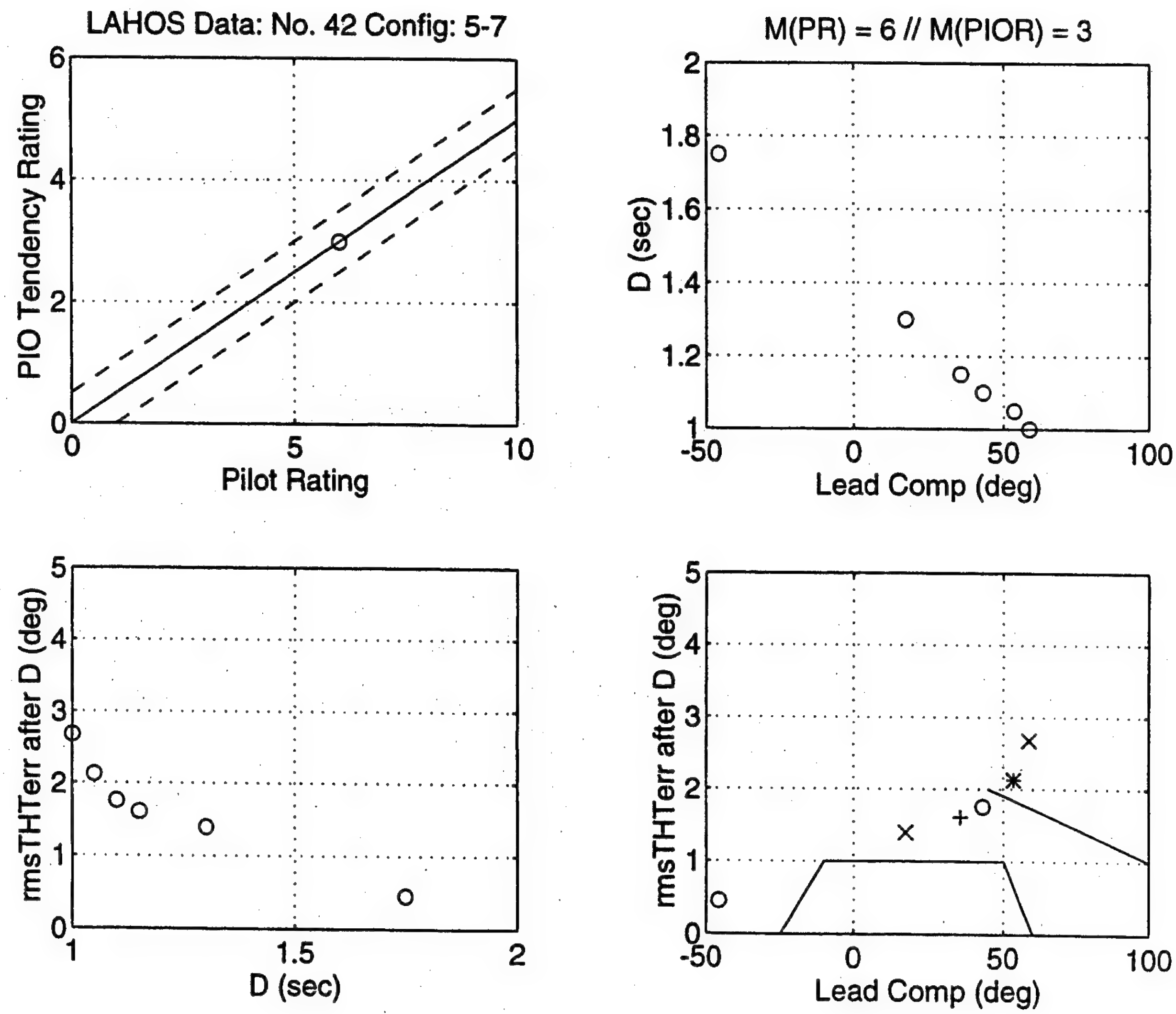
M(PR) = 6 // M(PIOR) = 3
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

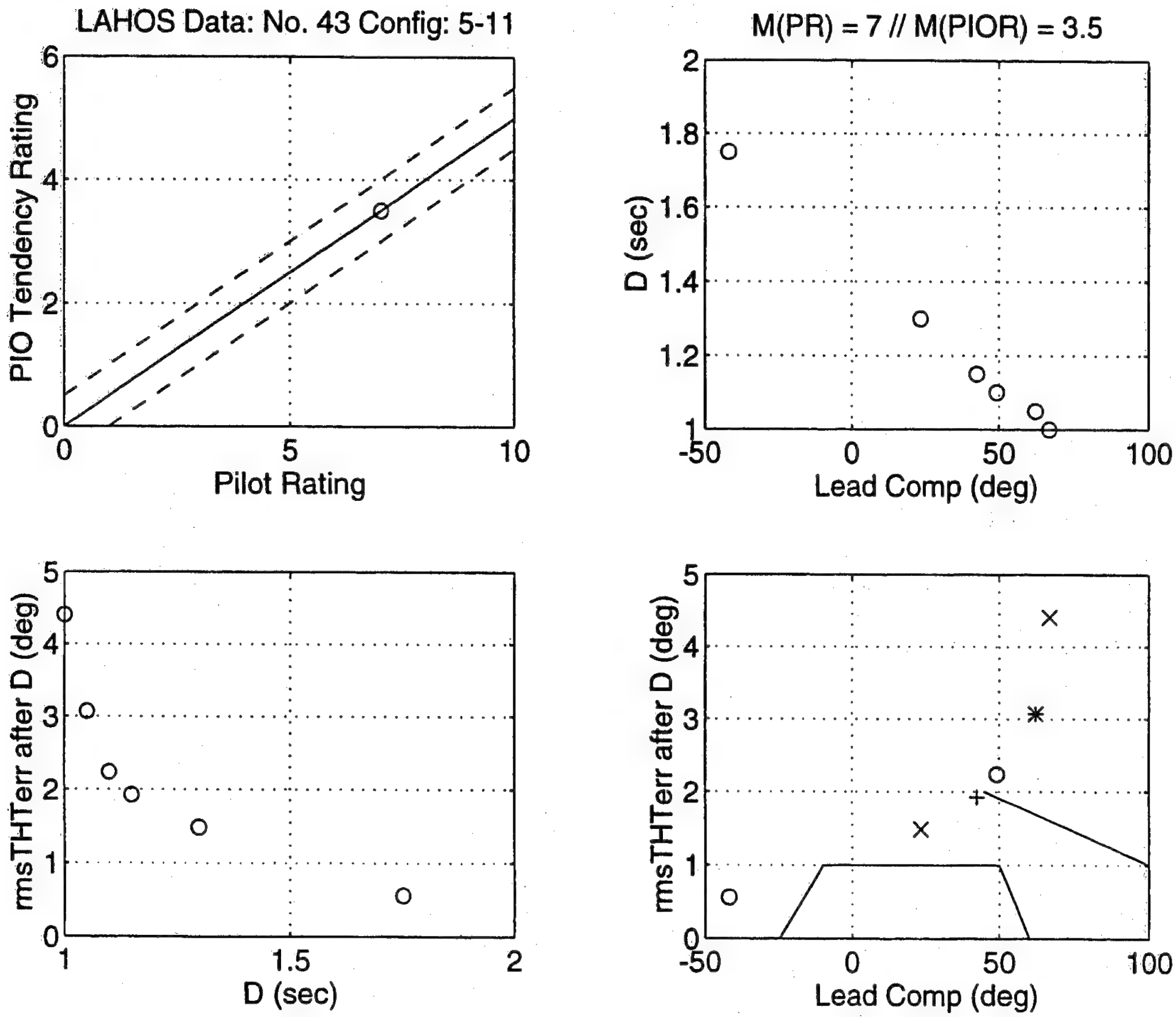


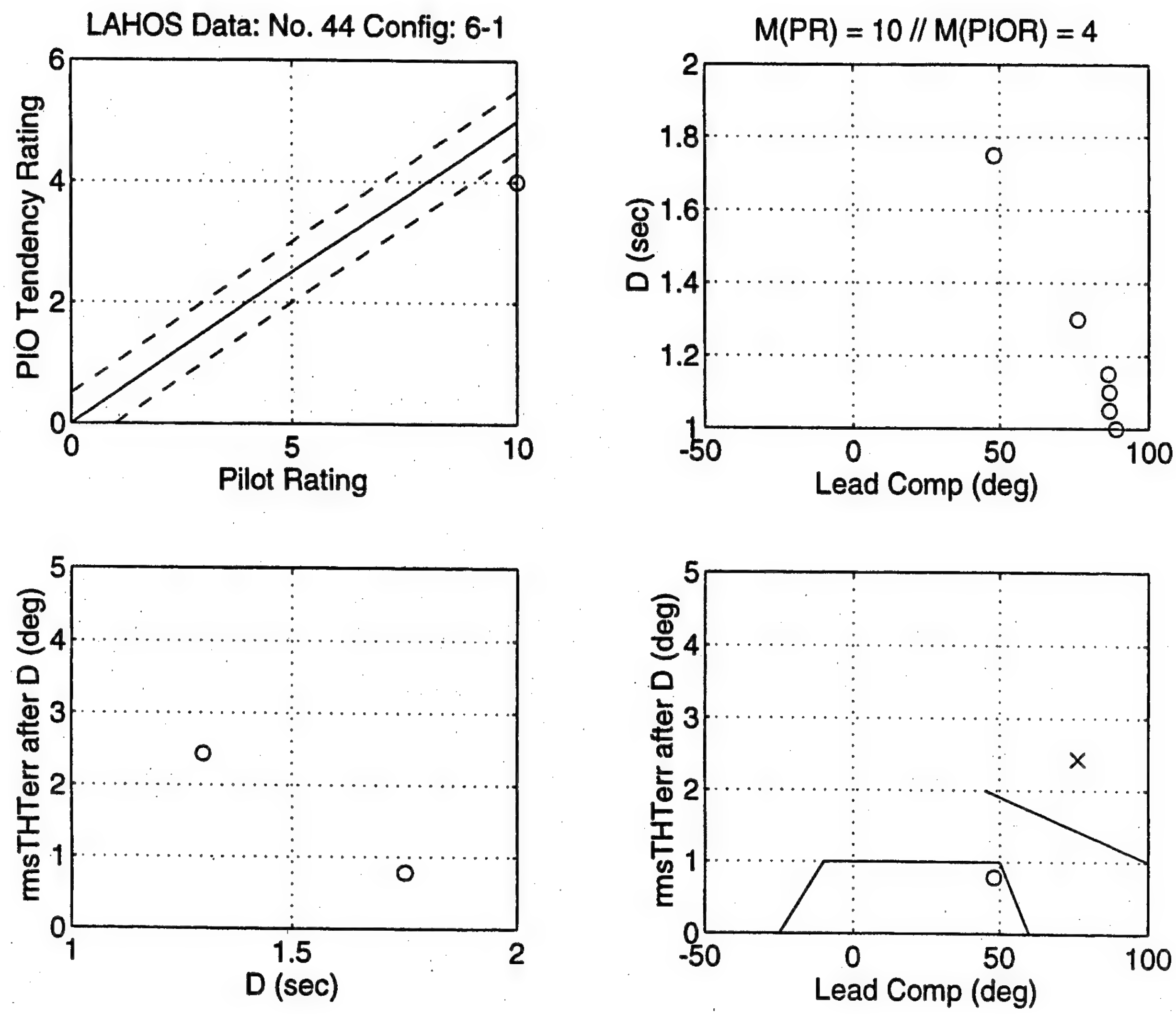
LAHOS Data: No. 39 Config: 5-4
PIO Tendency Rating
Pilot Rating
M(PR) = 6 // M(PIOR) = 2.5
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

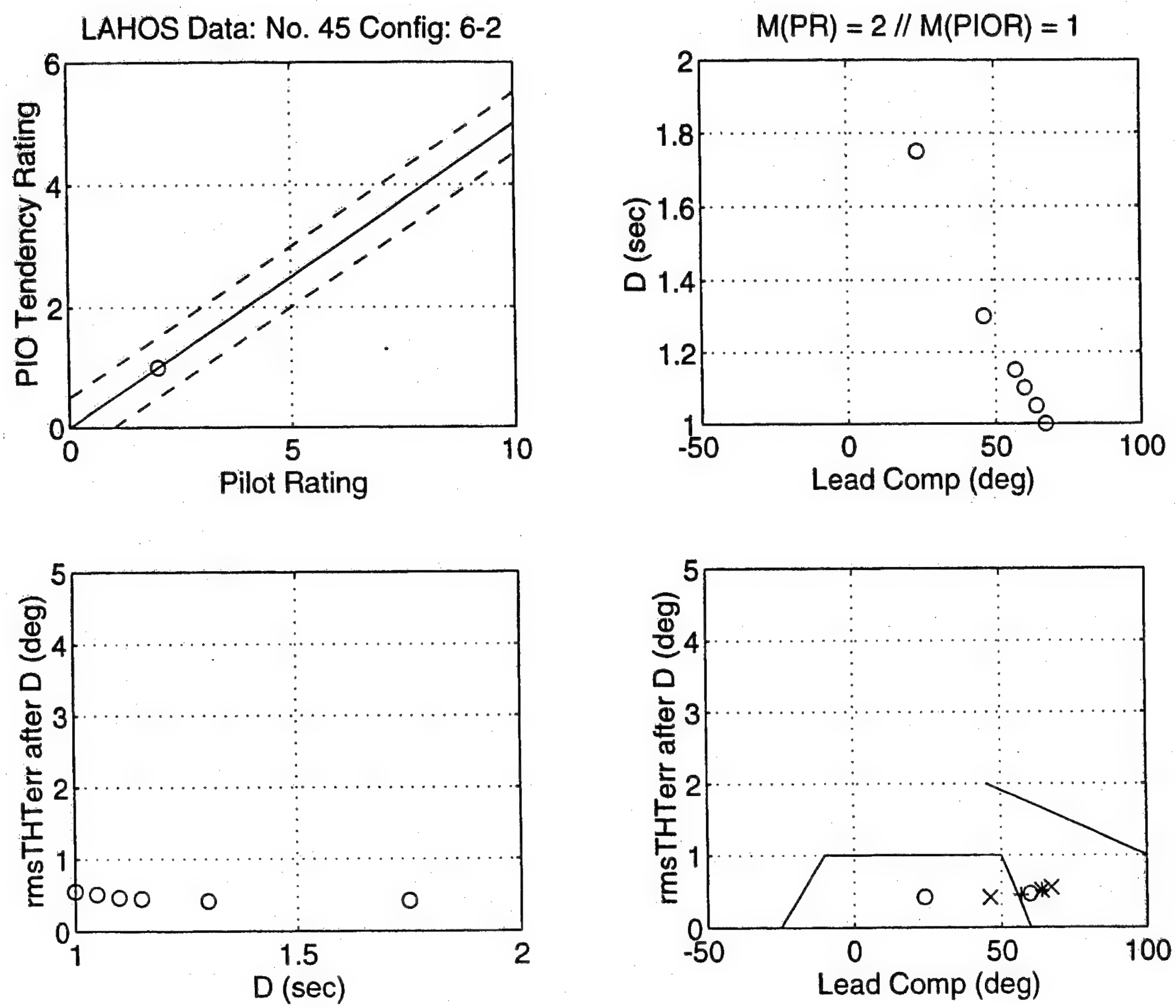

LAHOS Data: No. 41 Config: 5-6
PIO Tendency Rating
Pilot Rating
M(PR) = 6 // M(PIOR) = 3
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

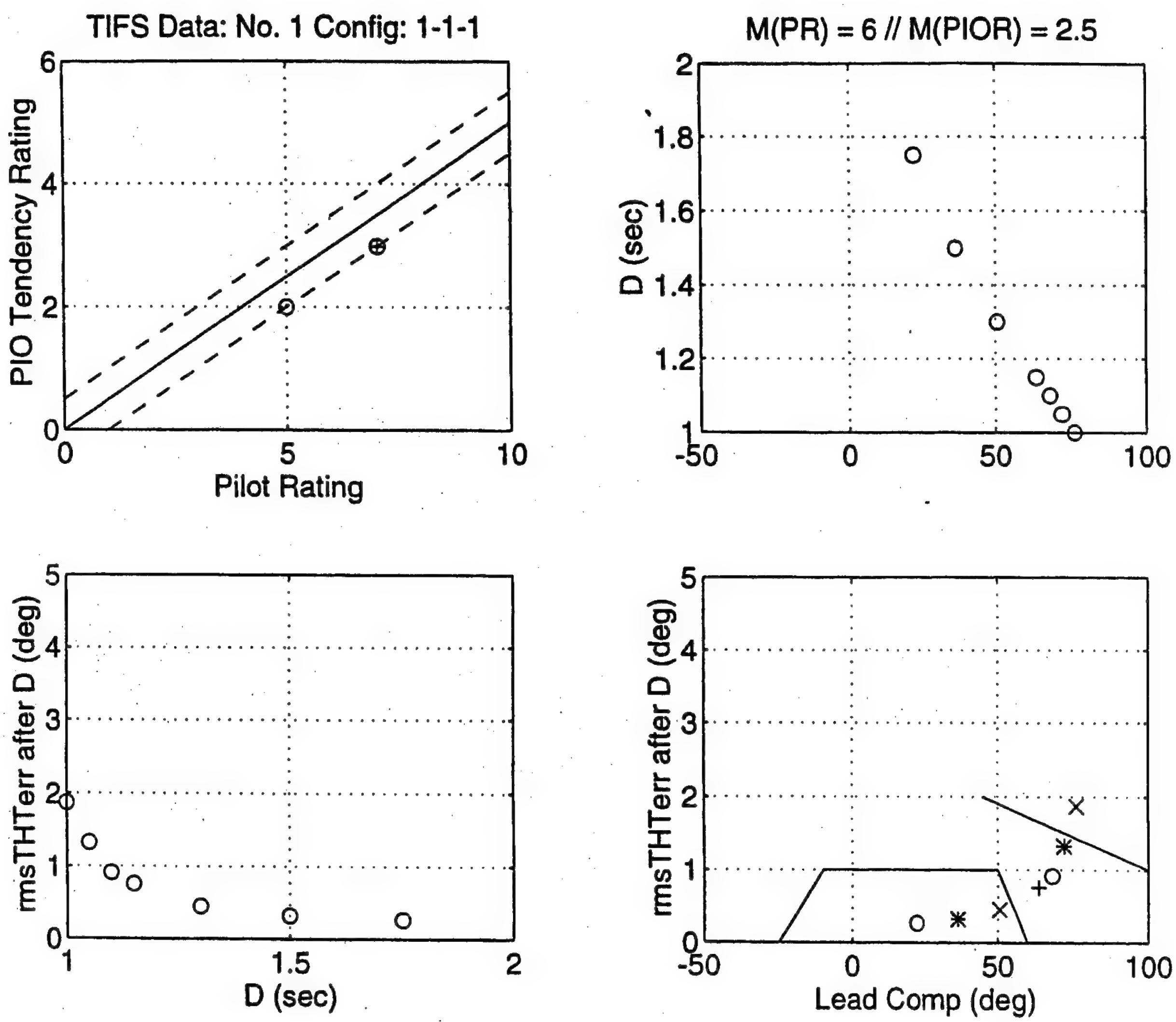


LAHOS Data: No. 42 Config: 5-7
PIO Tendency Rating
Pilot Rating
M(PR) = 6 // M(PIOR) = 3
D (sec)
Lead Comp (deg)
msTHTerr after D (deg)
D (sec)
msTHTerr after D (deg)
Lead Comp (deg)

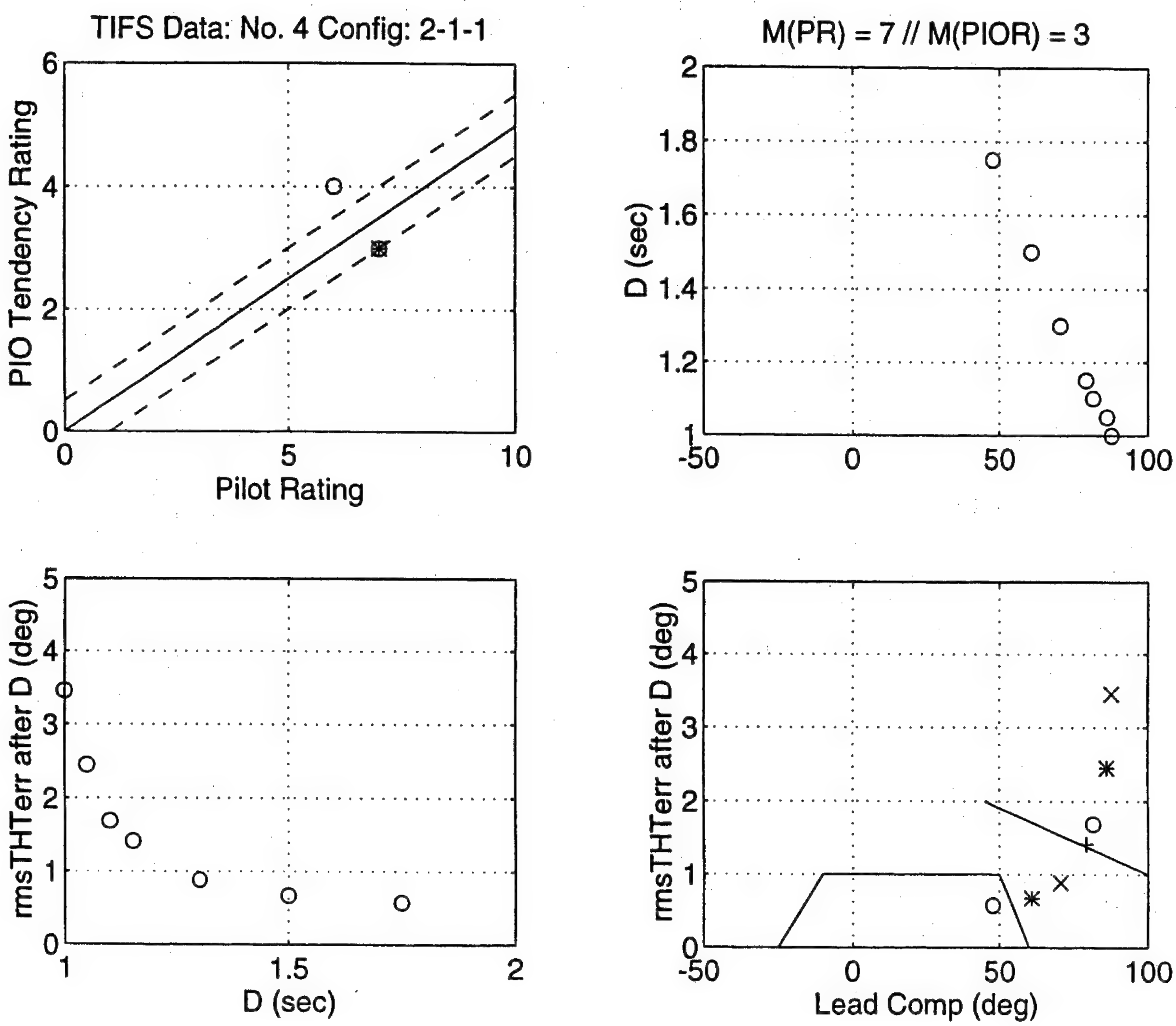

LAHOS Data: No. 43 Config: 5-11
M(PR) = 7 // M(PIOR) = 3.5
PIO Tendency Rating
Pilot Rating
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


LAHOS Data: No. 44 Config: 6-1
PIO Tendency Rating
Pilot Rating
M(PR) = 10 // M(PIOR) = 4
D (sec)
Lead Comp (deg)
msTHTerr after D (deg)
D (sec)
msTHTerr after D (deg)
Lead Comp (deg)

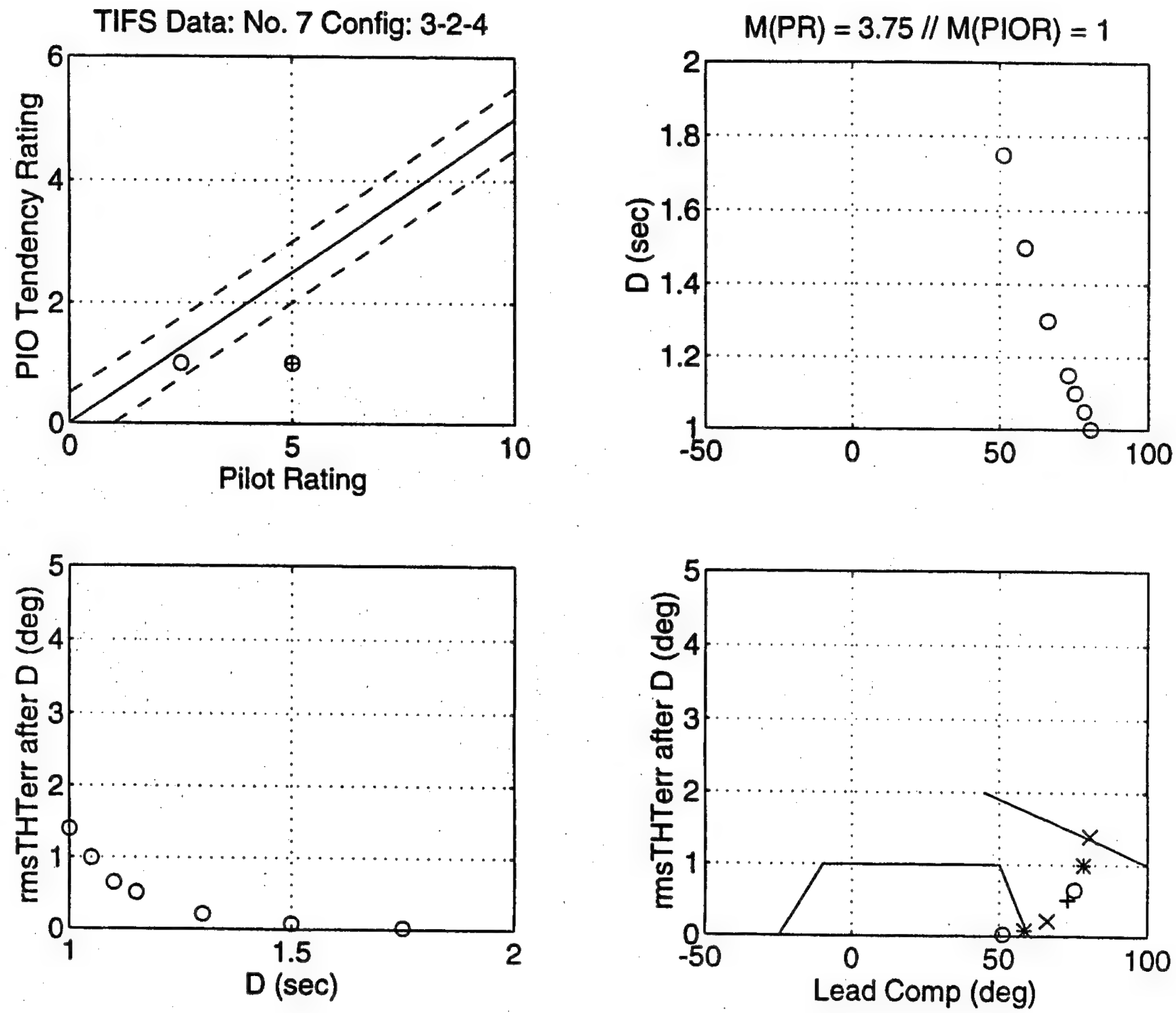

LAHOS Data: No. 45 Config: 6-2
PIO Tendency Rating
Pilot Rating
M(PR) = 2 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)



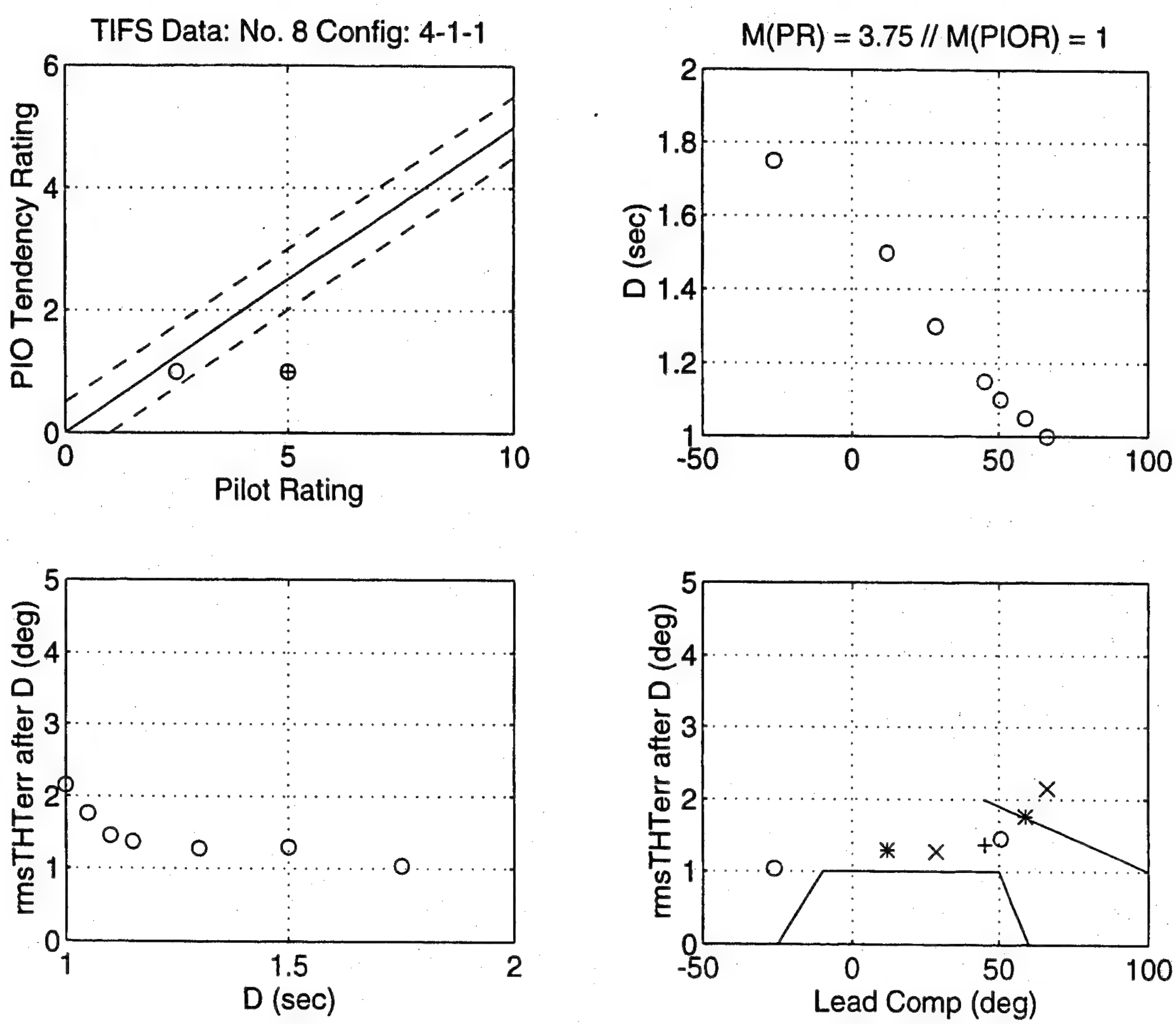
TIFS Data: No. 1 Config: 1-1-1
PIO Tendency Rating
Pilot Rating
0
2
4
6
5
10
M(PR) = 6 // M(PIOR) = 2.5
D (sec)
1
1.2
1.4
1.6
1.8
2
-50
50
100
msTHTerr after D (deg)
D (sec)
1.5
3
msTHTerr after D (deg)
Lead Comp (deg)

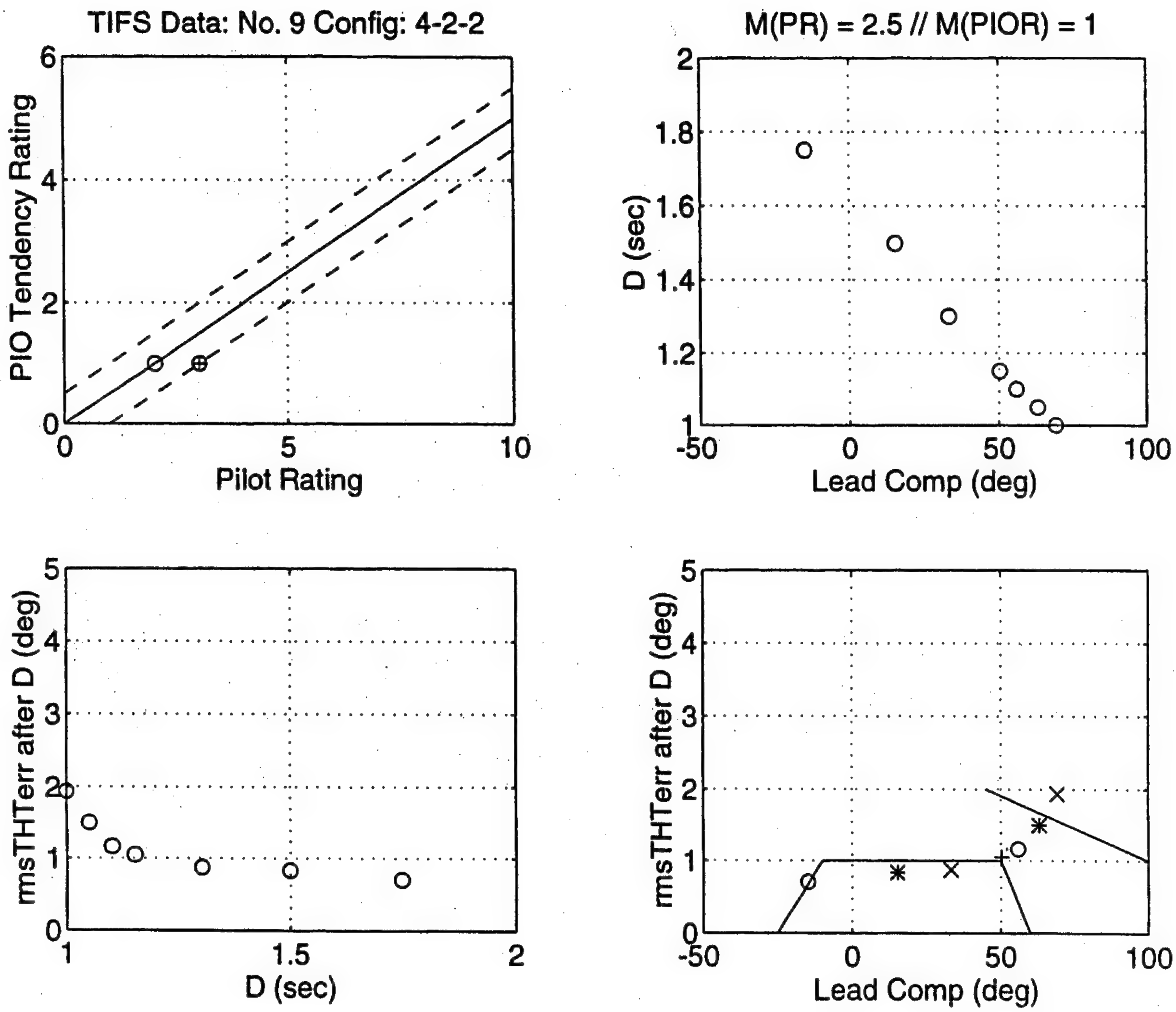


TIFS Data: No. 4 Config: 2-1-1
PIO Tendency Rating
Pilot Rating
M(PR) = 7 // M(PIOR) = 3
D (sec)
msTHTerr after D (deg)
D (sec)
msTHTerr after D (deg)
Lead Comp (deg)

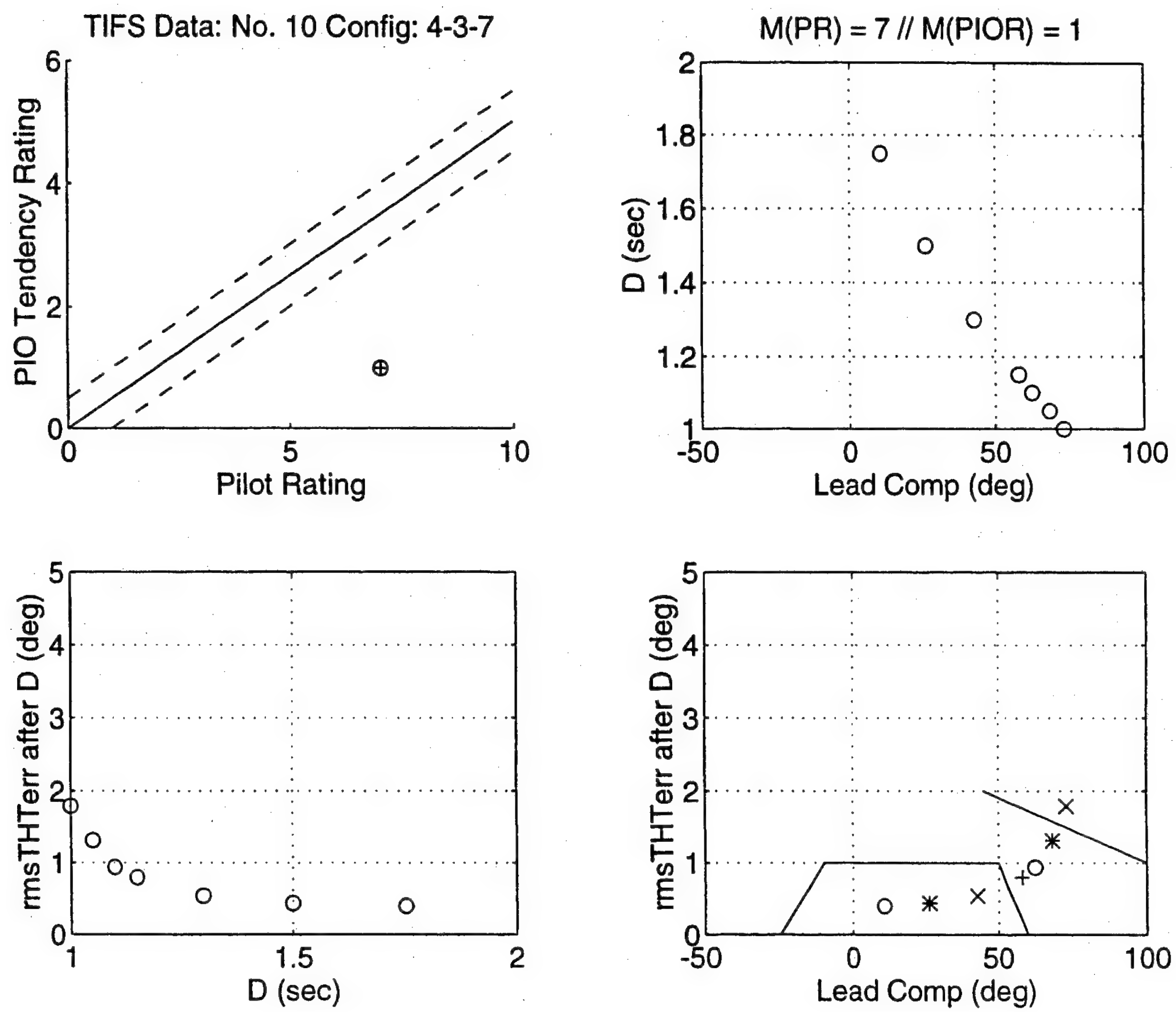


TIFS Data: No. 7 Config: 3-2-4
PIO Tendency Rating
Pilot Rating
M(PR) = 3.75 // M(PIOR) = 1
D (sec)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

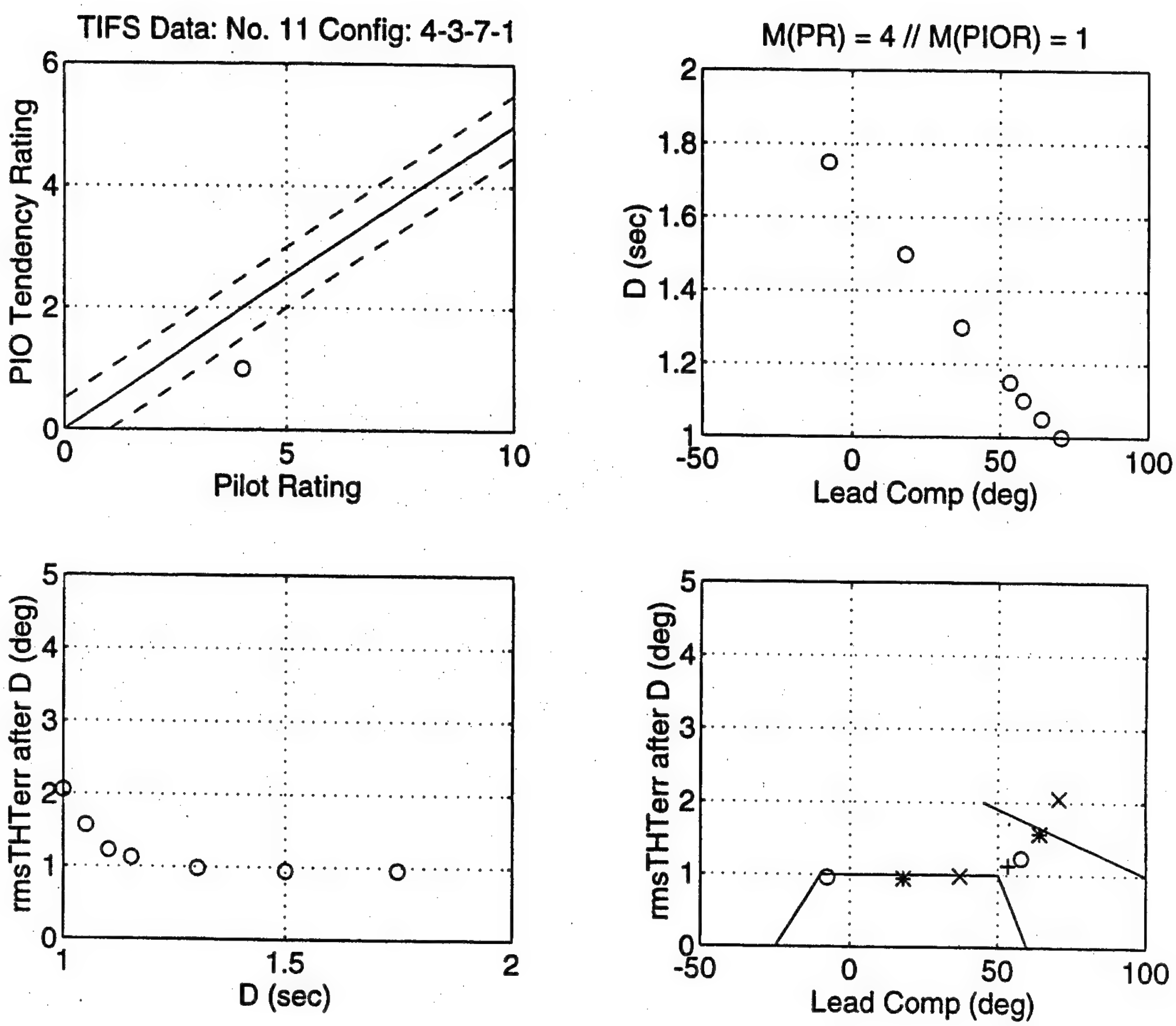

TIFS Data: No. 8 Config: 4-1-1
PIO Tendency Rating
Pilot Rating
M(PR) = 3.75 // M(PIOR) = 1
D (sec)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

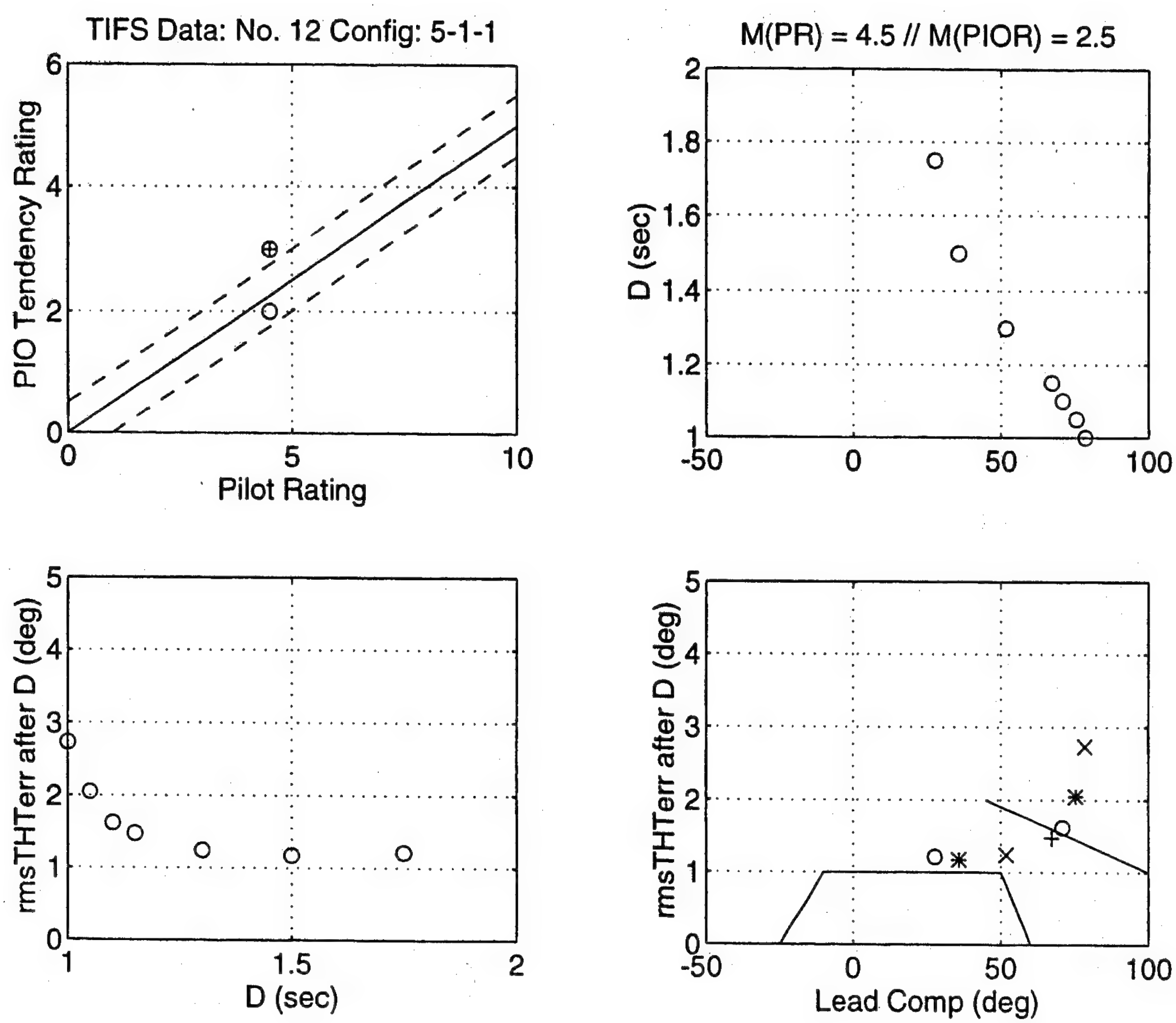


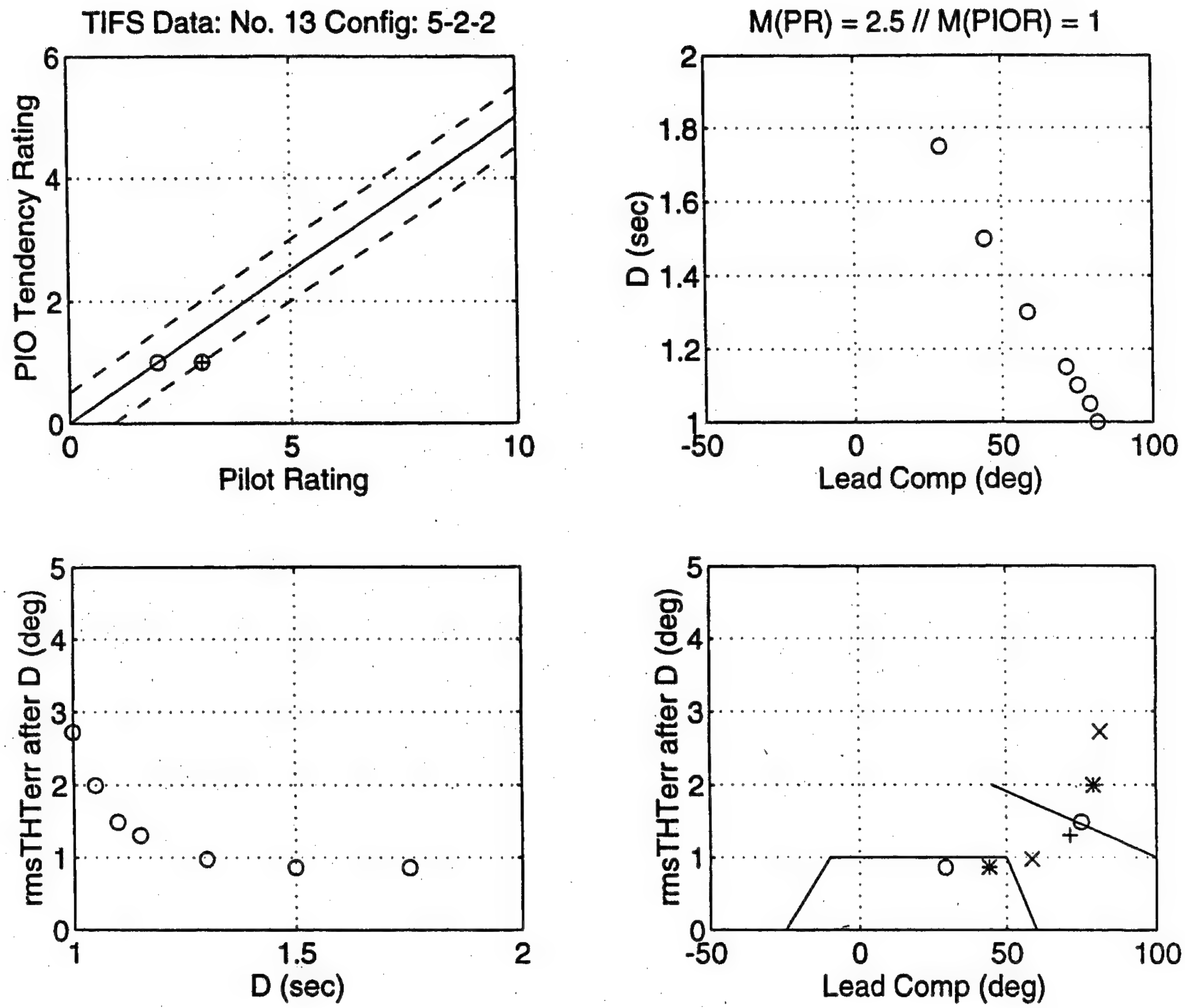
TIFS Data: No. 9 Config: 4-2-2
PIO Tendency Rating
Pilot Rating
M(PR) = 2.5 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
msTHTerr after D (deg)
D (sec)
msTHTerr after D (deg)
Lead Comp (deg)

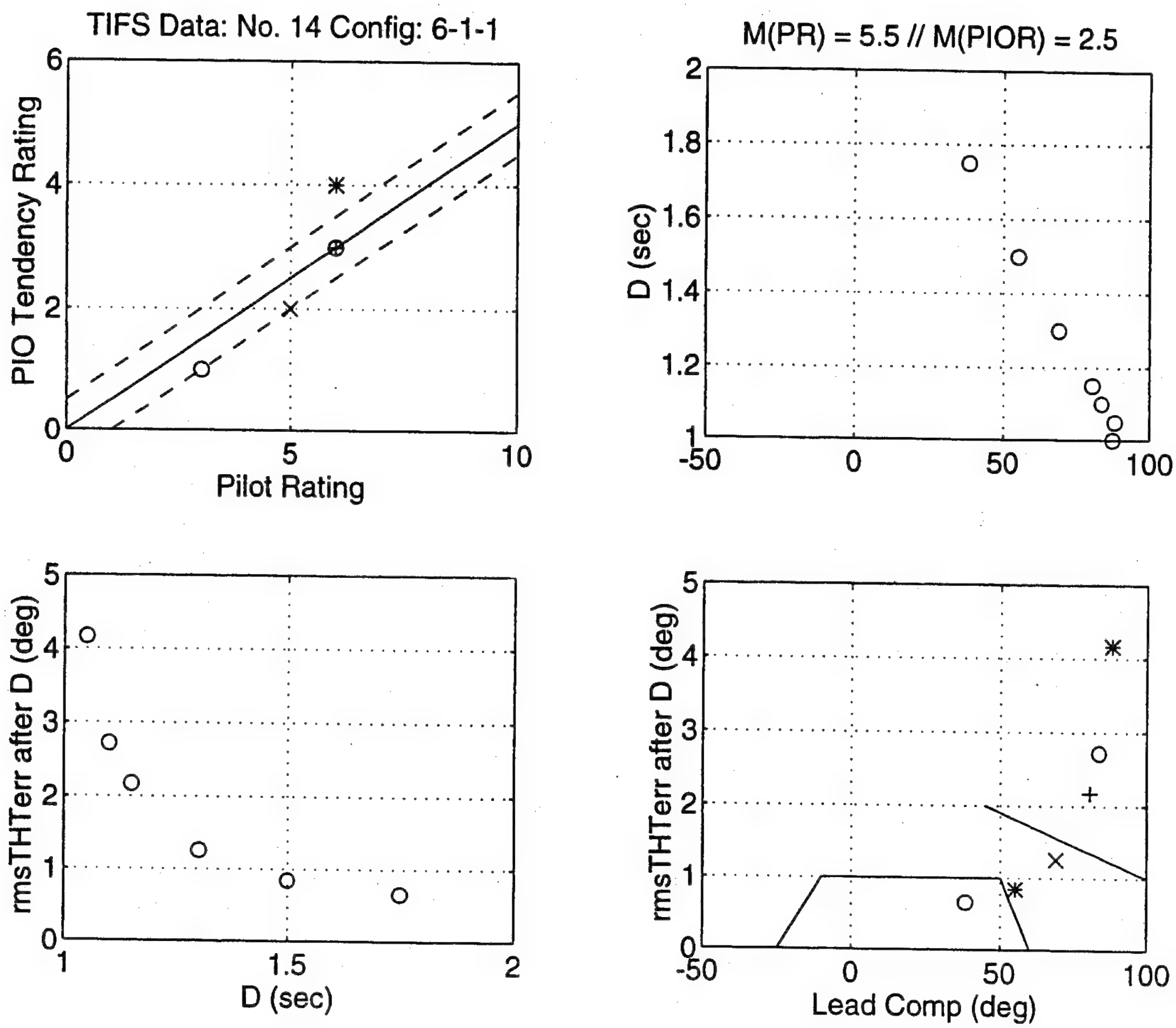


TIFS Data: No. 10 Config: 4-3-7
PIO Tendency Rating
Pilot Rating
M(PR) = 7 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

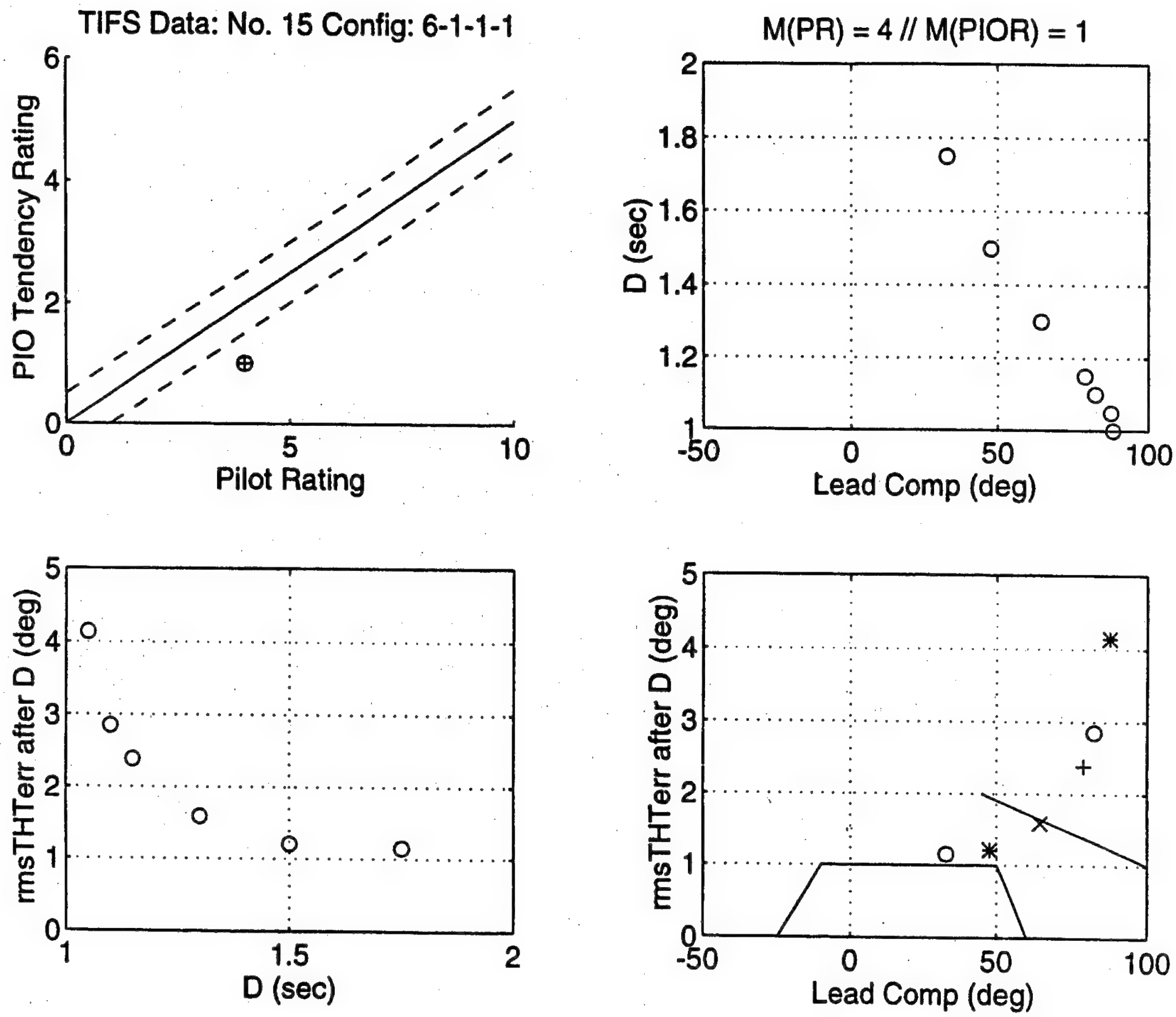

TIFS Data: No. 11 Config: 4-3-7-1
PIO Tendency Rating
Pilot Rating
M(PR) = 4 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


TIFS Data: No. 12 Config: 5-1-1
PIO Tendency Rating
Pilot Rating
M(PR) = 4.5 // M(PIOR) = 2.5
D (sec)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

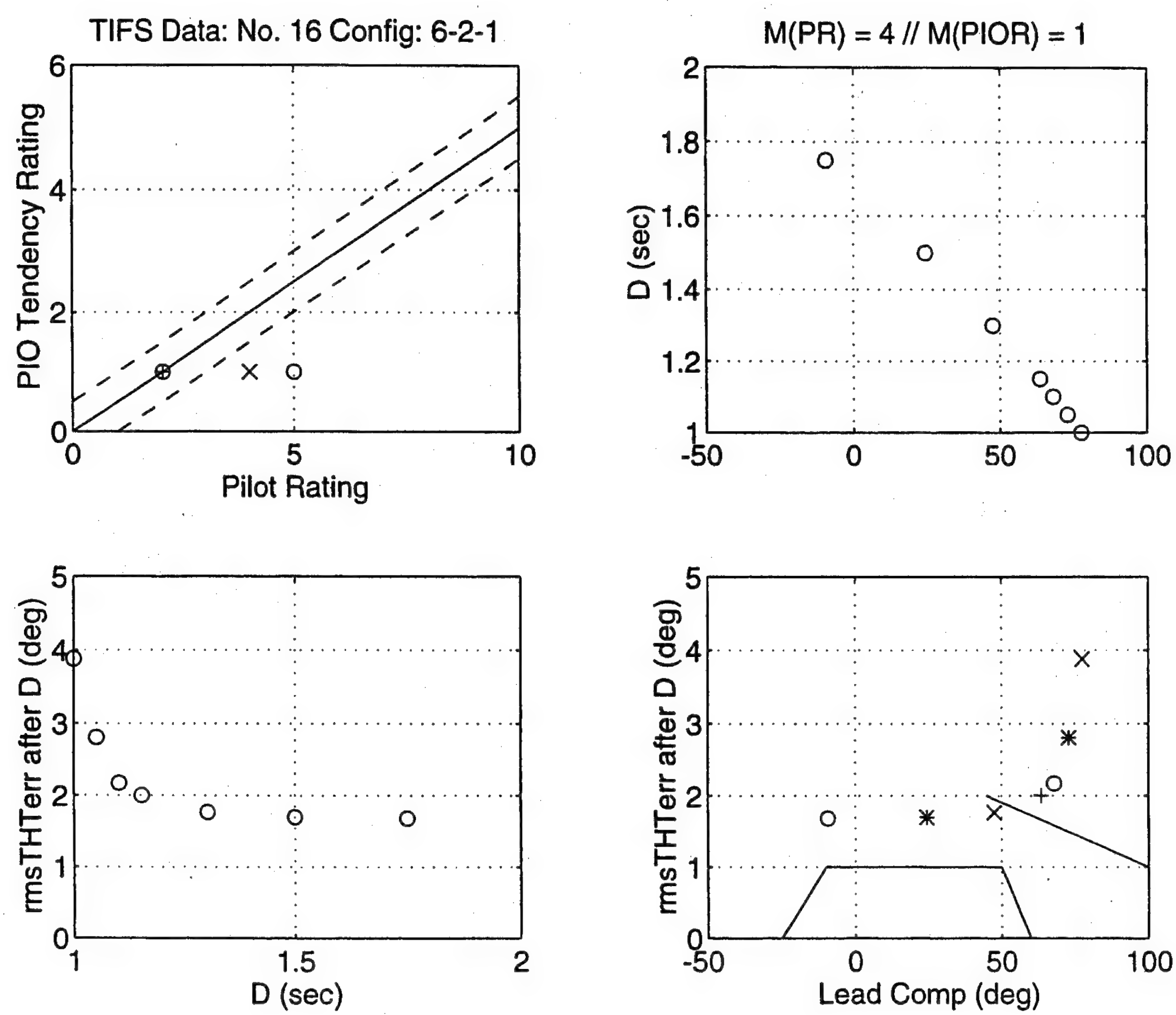

TIFS Data: No. 13 Config: 5-2-2
PIO Tendency Rating
Pilot Rating
M(PR) = 2.5 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

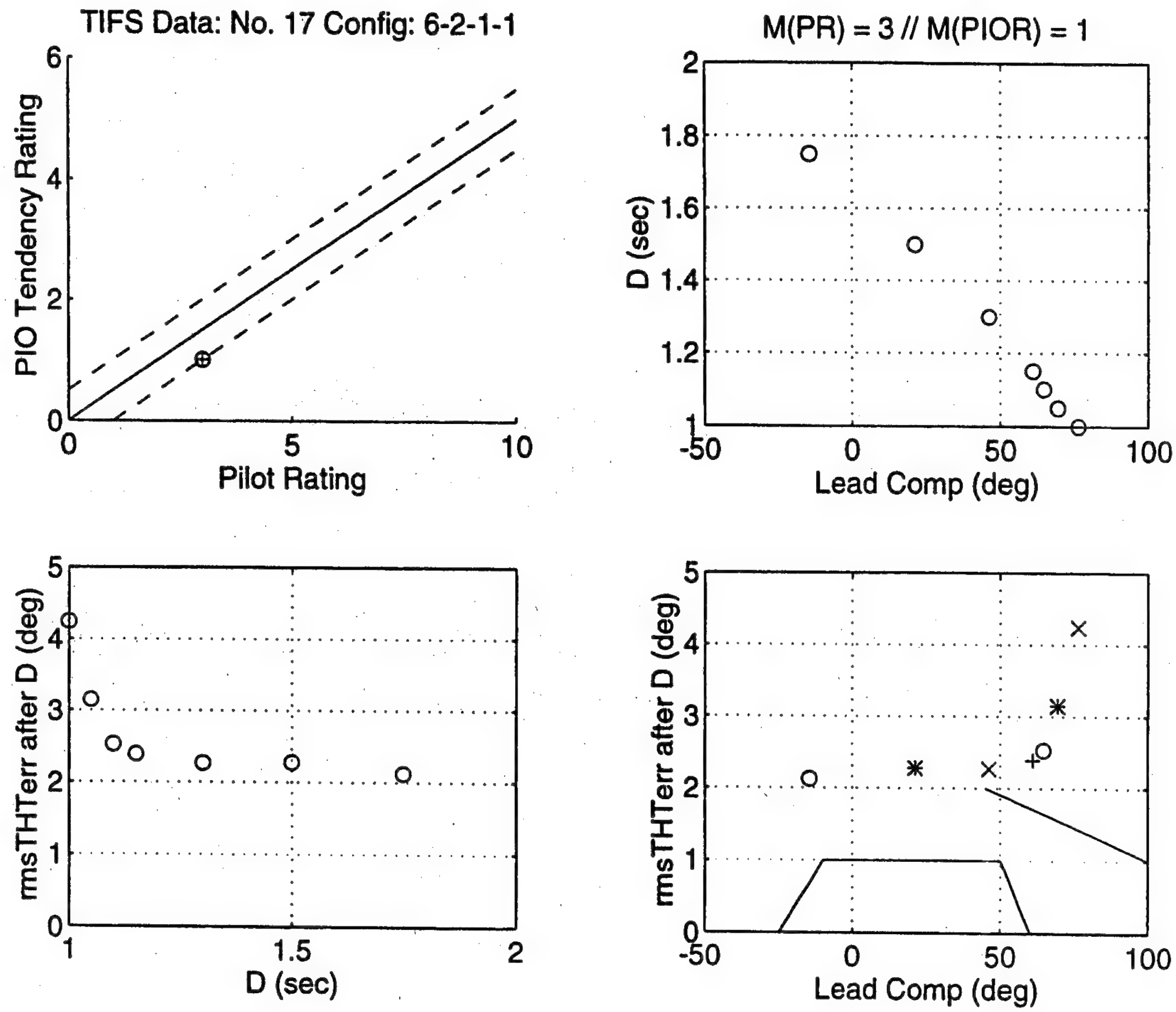


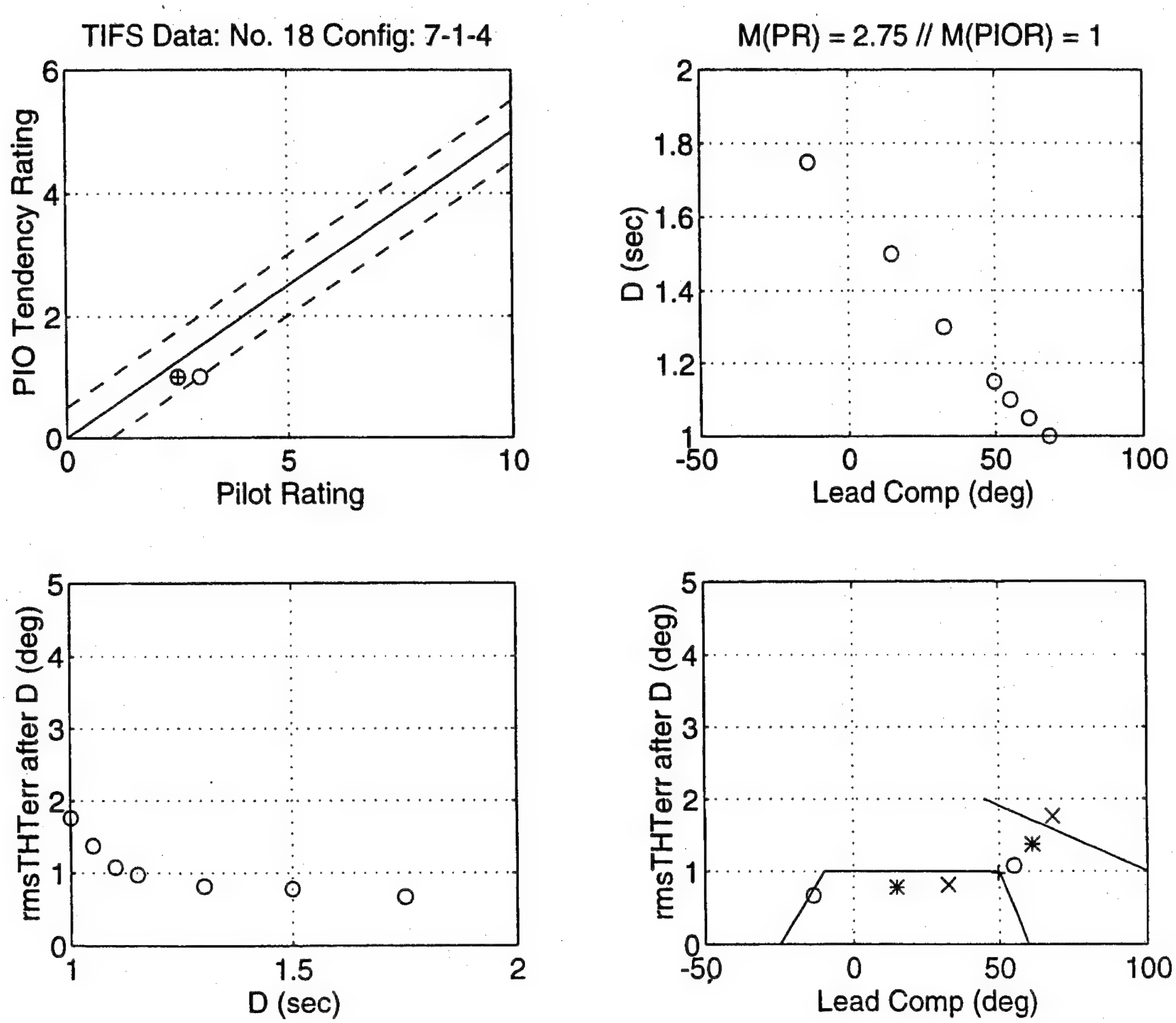
TIFS Data: No. 14 Config: 6-1-1
PIO Tendency Rating
Pilot Rating
M(PR) = 5.5 // M(PIOR) = 2.5
D (sec)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

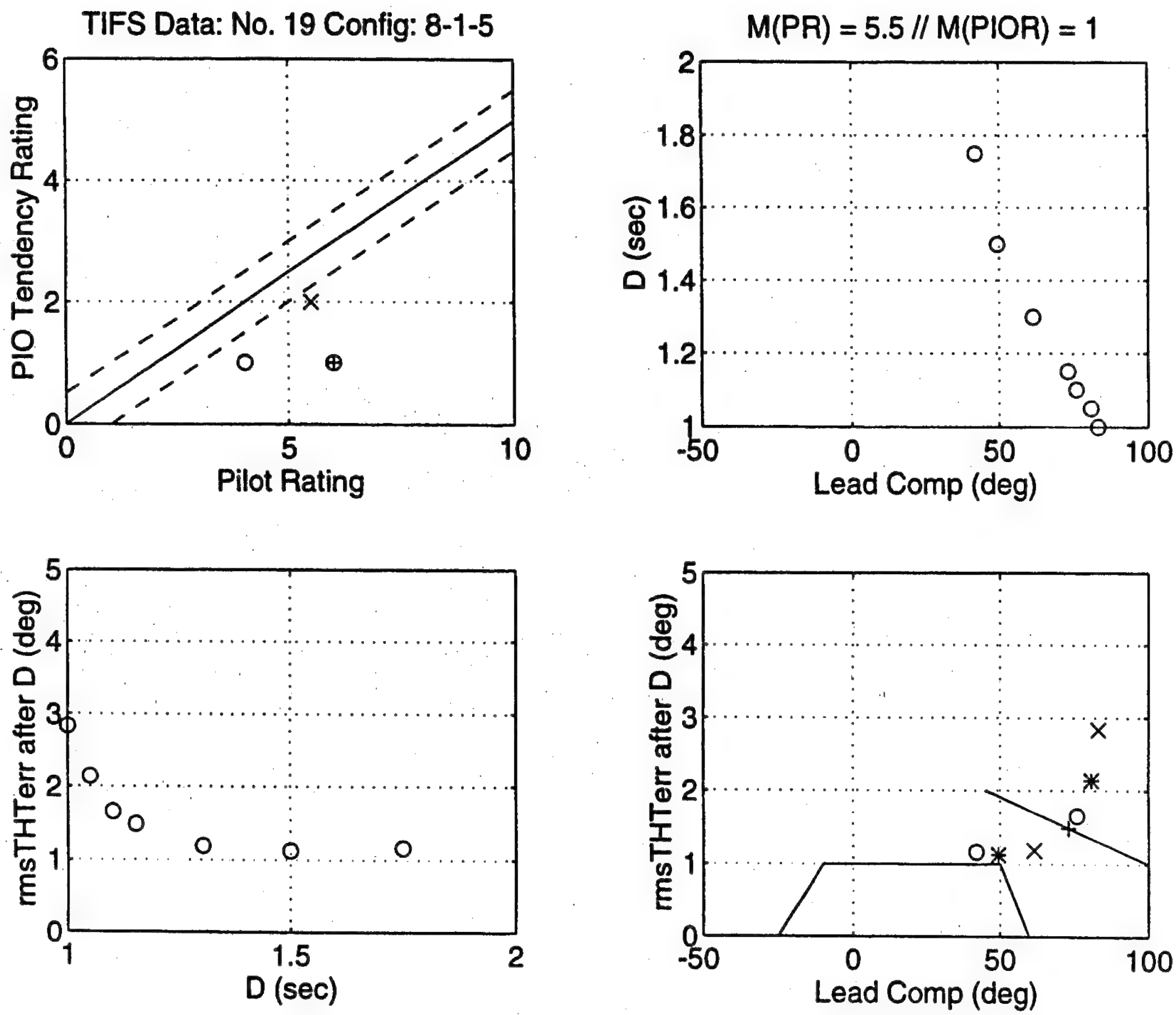


TIFS Data: No. 15 Config: 6-1-1-1
PIO Tendency Rating
Pilot Rating
M(PR) = 4 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
msTHTerr after D (deg)
D (sec)
msTHTerr after D (deg)
Lead Comp (deg)

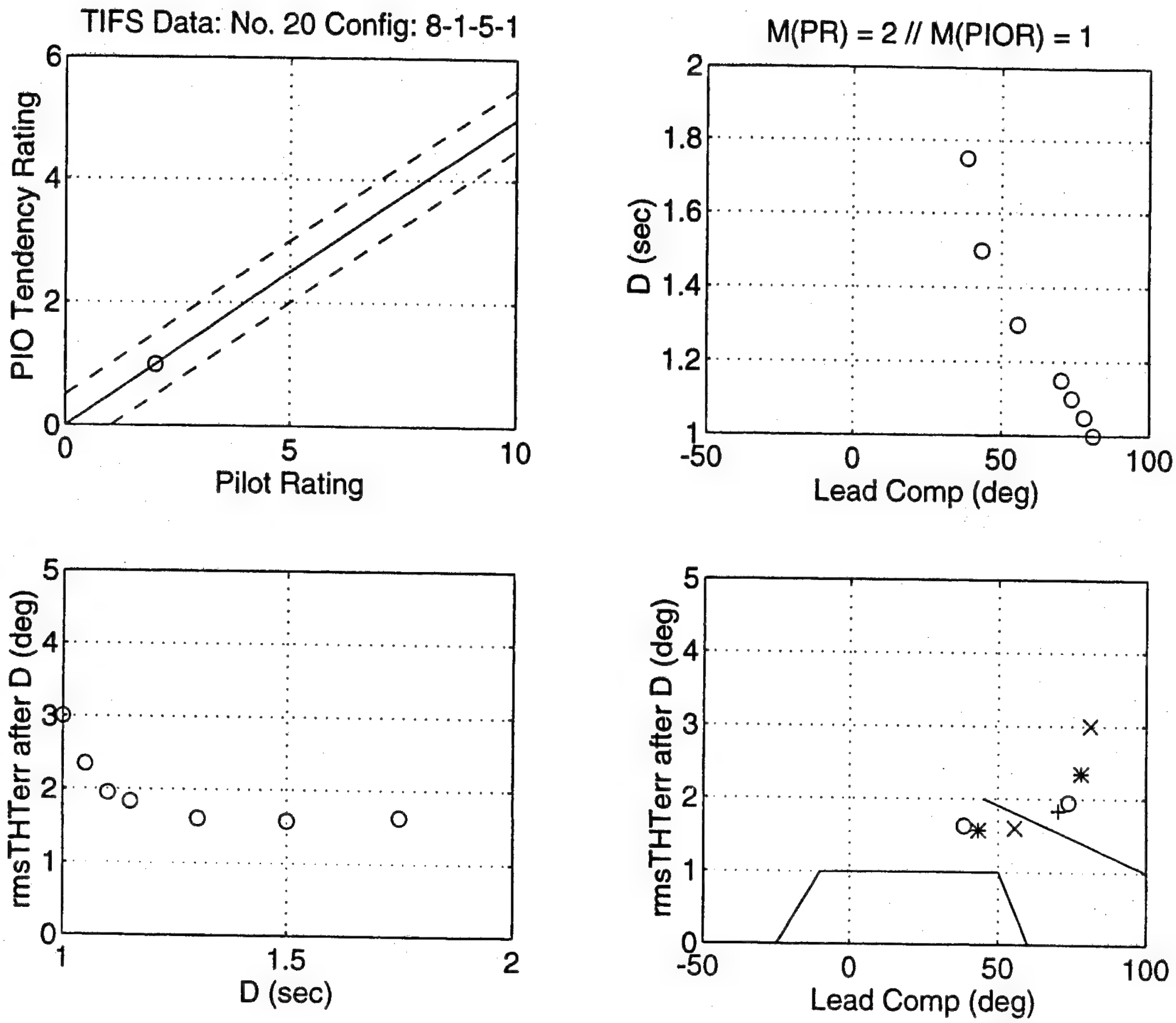

TIFS Data: No. 16 Config: 6-2-1
M(PR) = 4 // M(PIOR) = 1
PIO Tendency Rating
Pilot Rating
D (sec)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

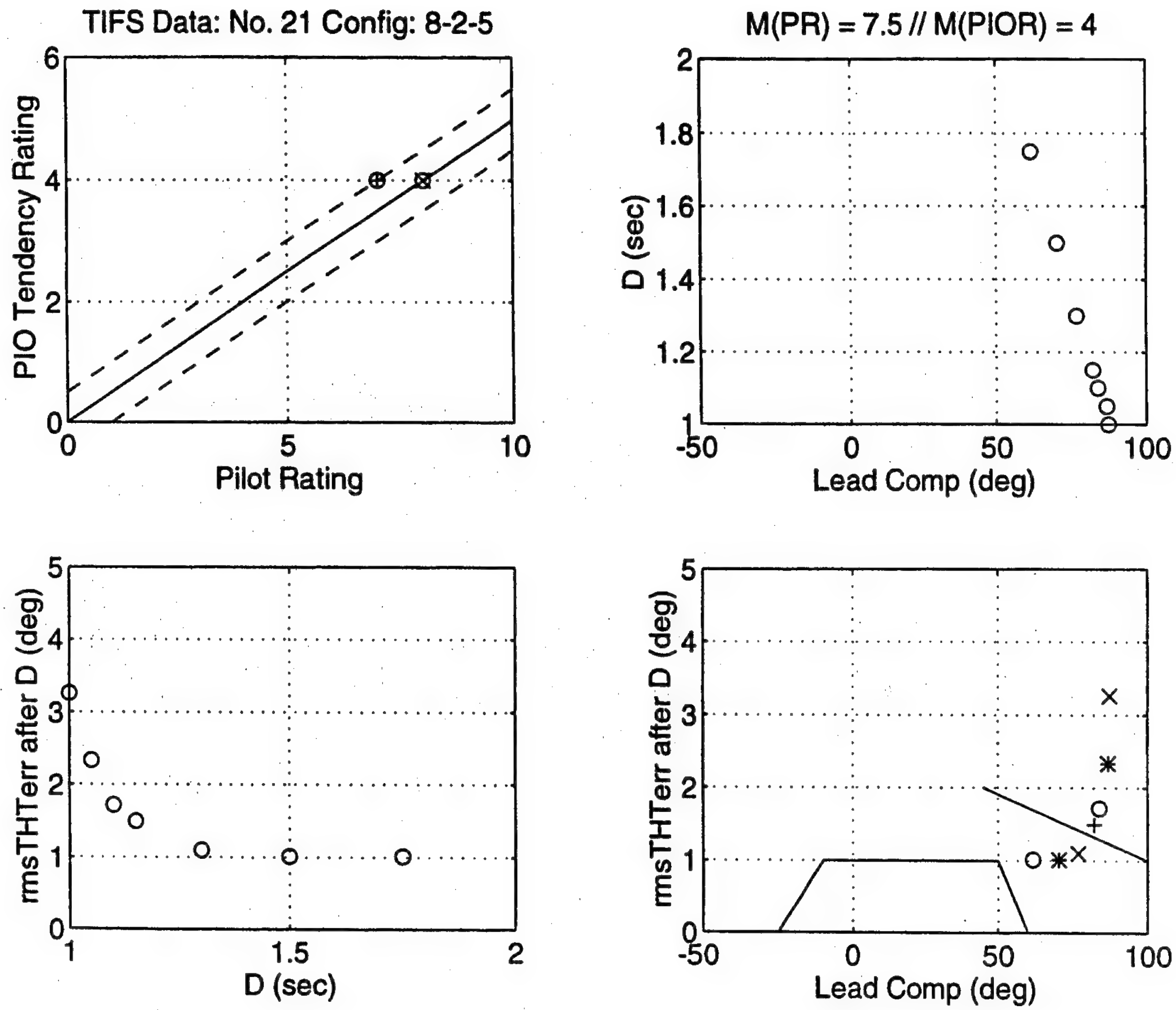

TIFS Data: No. 17 Config: 6-2-1-1
PIO Tendency Rating
Pilot Rating
M(PR) = 3 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


TIFS Data: No. 18 Config: 7-1-4
PIO Tendency Rating
Pilot Rating
M(PR) = 2.75 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

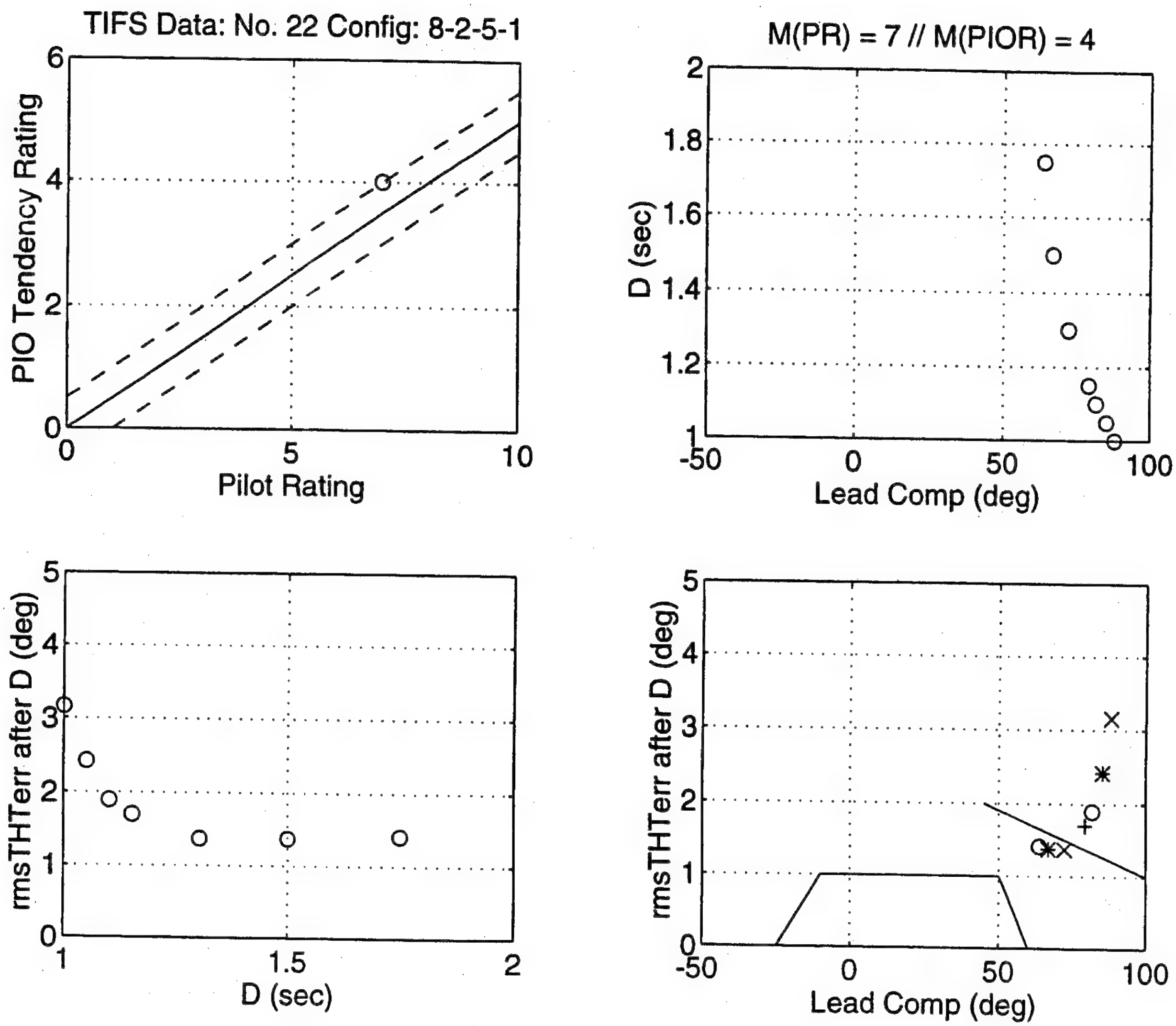


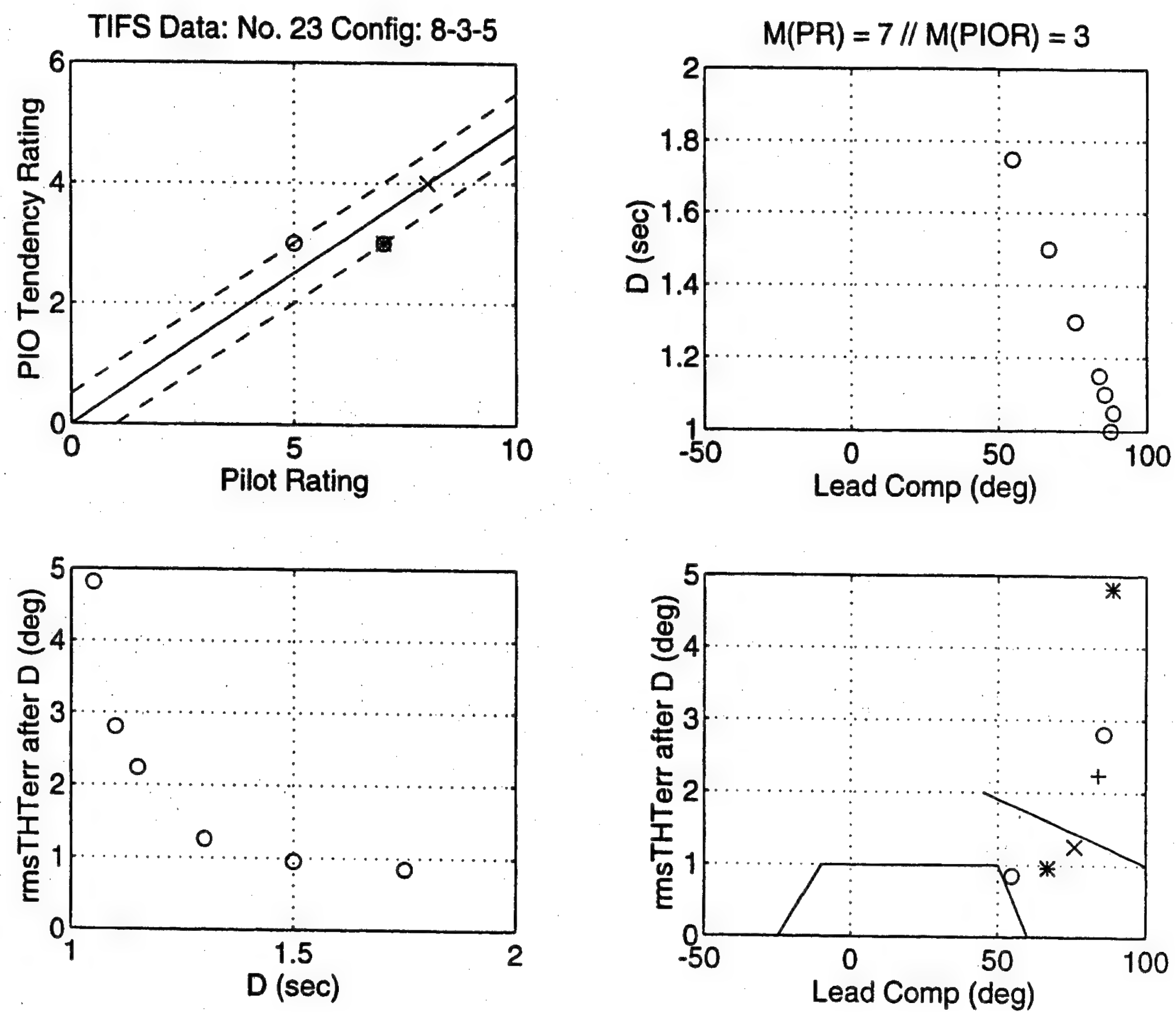
TIFS Data: No. 19 Config: 8-1-5
PIO Tendency Rating
Pilot Rating
M(PR) = 5.5 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

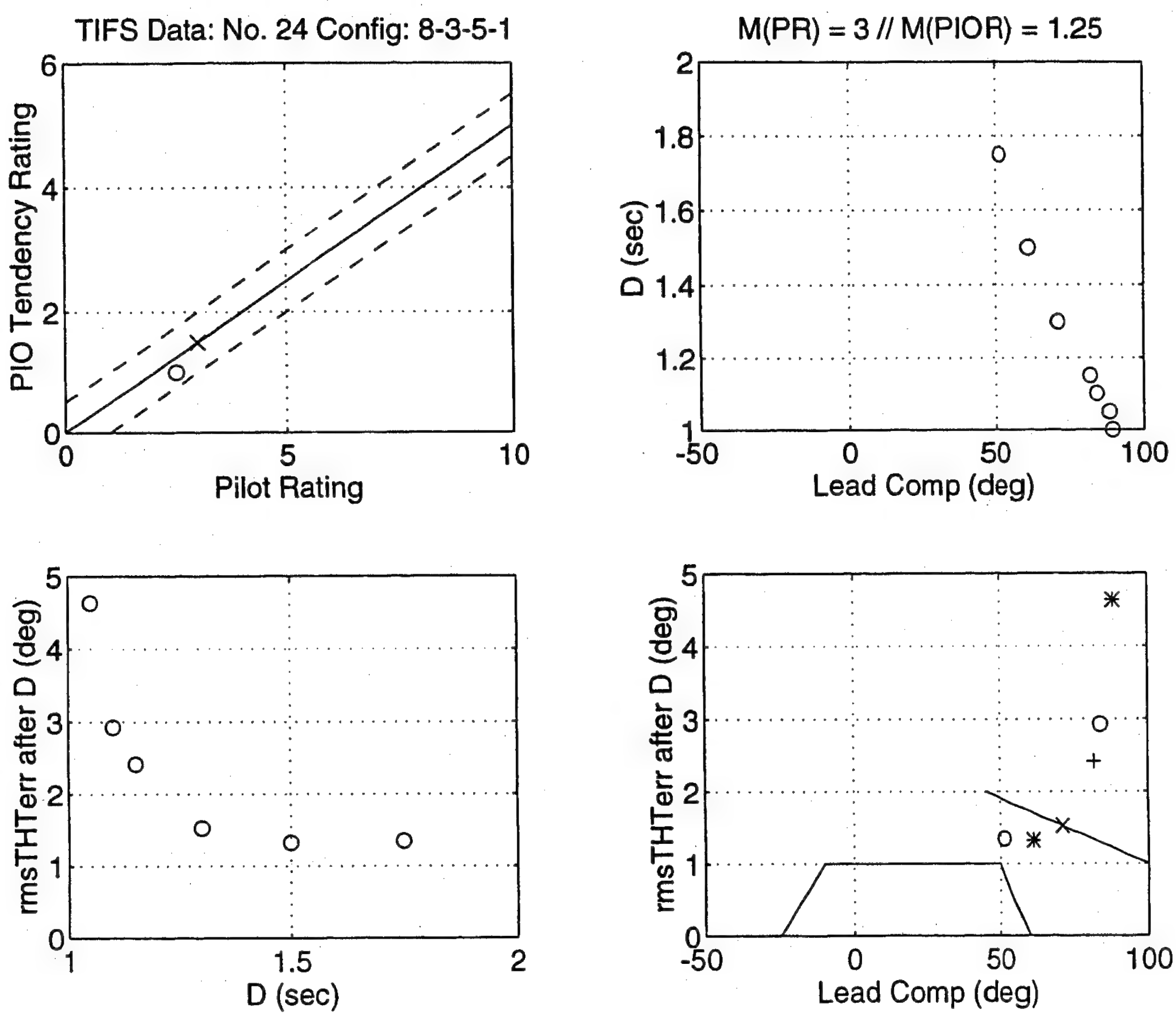

TIFS Data: No. 20 Config: 8-1-5-1
M(PR) = 2 // M(PIOR) = 1
PIO Tendency Rating
Pilot Rating
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

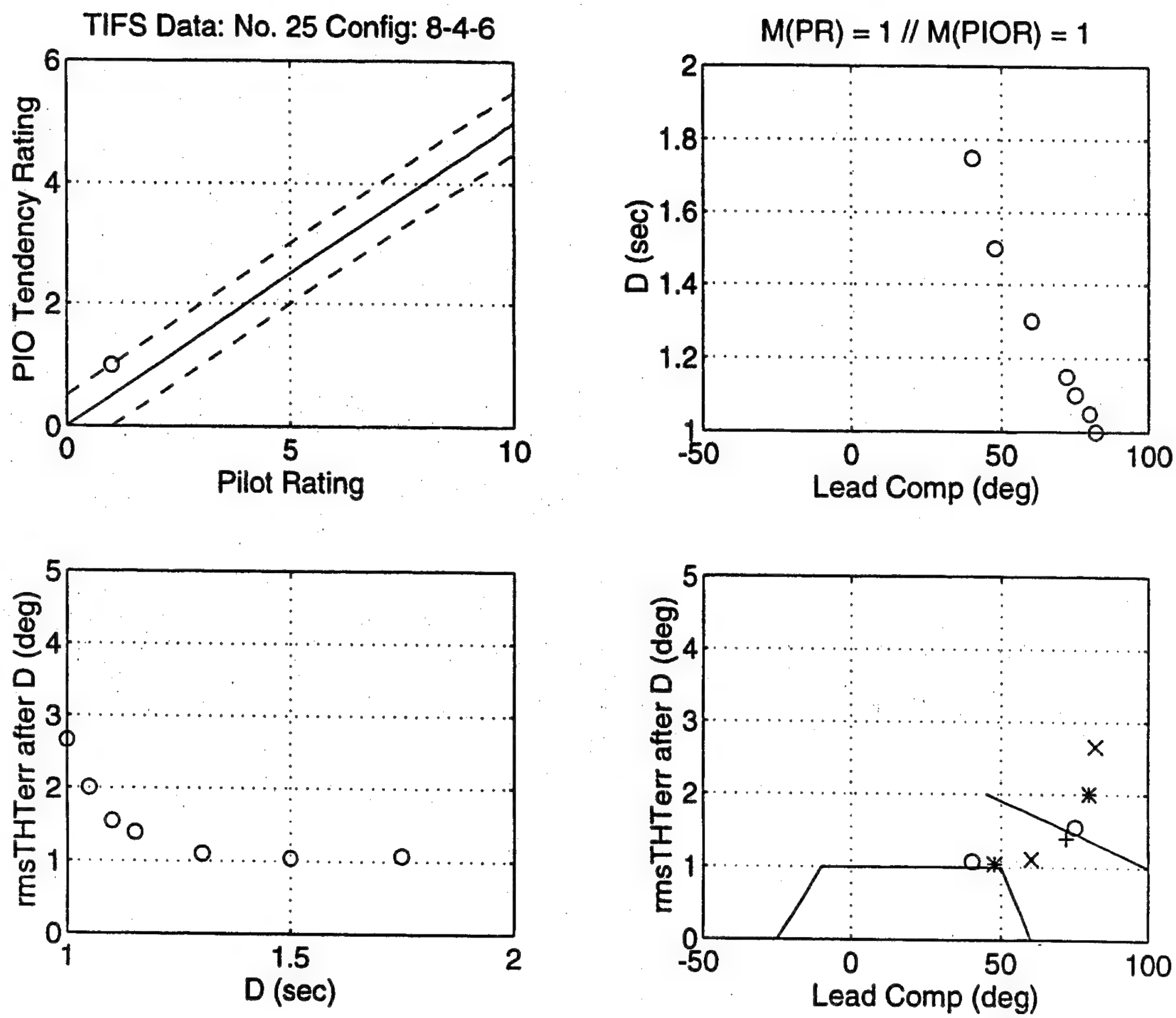


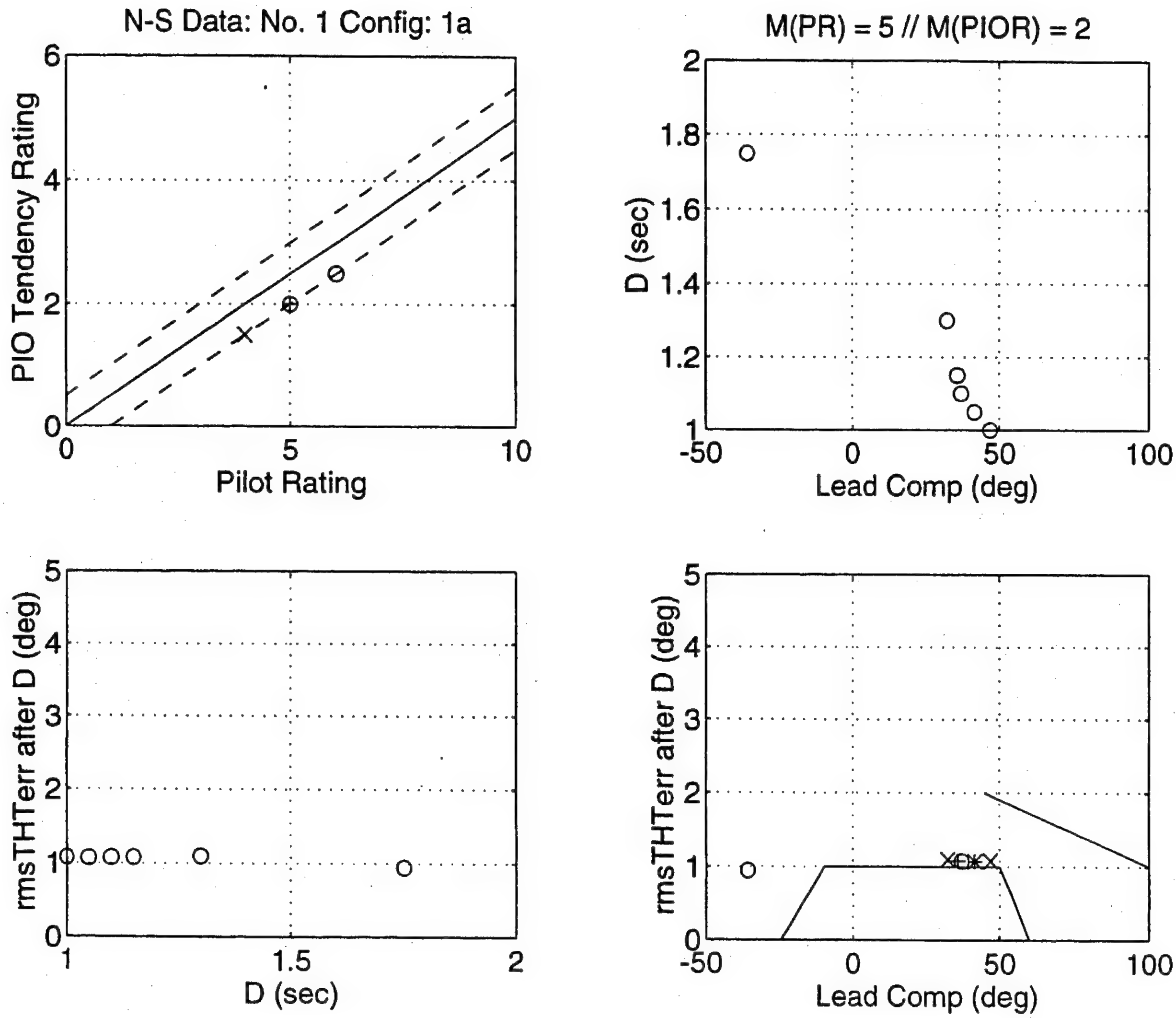
TIFS Data: No. 21 Config: 8-2-5
PIO Tendency Rating
Pilot Rating
M(PR) = 7.5 // M(PIOR) = 4
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

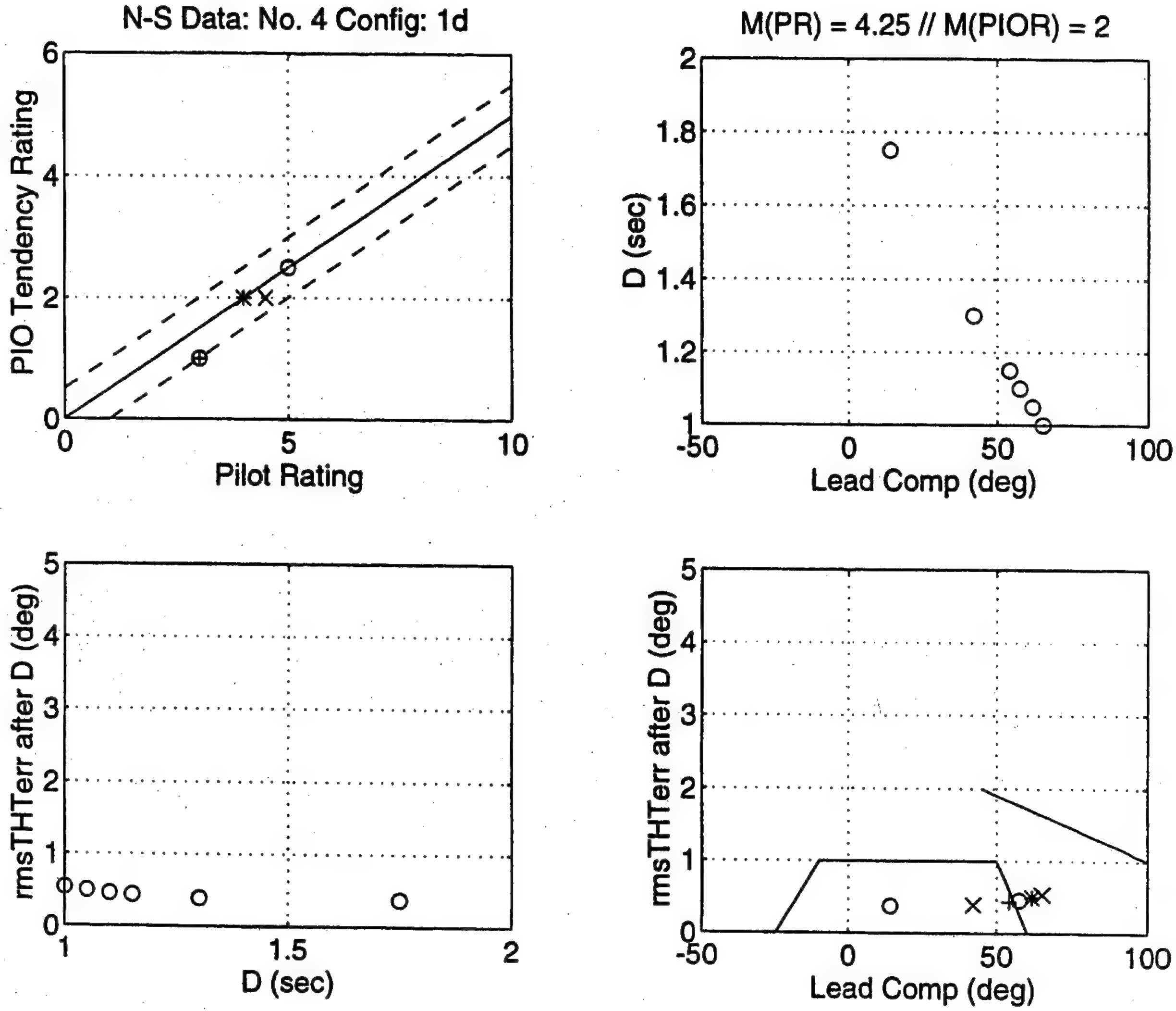

TIFS Data: No. 22 Config: 8-2-5-1
M(PR) = 7 // M(PIOR) = 4
PIO Tendency Rating
Pilot Rating
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

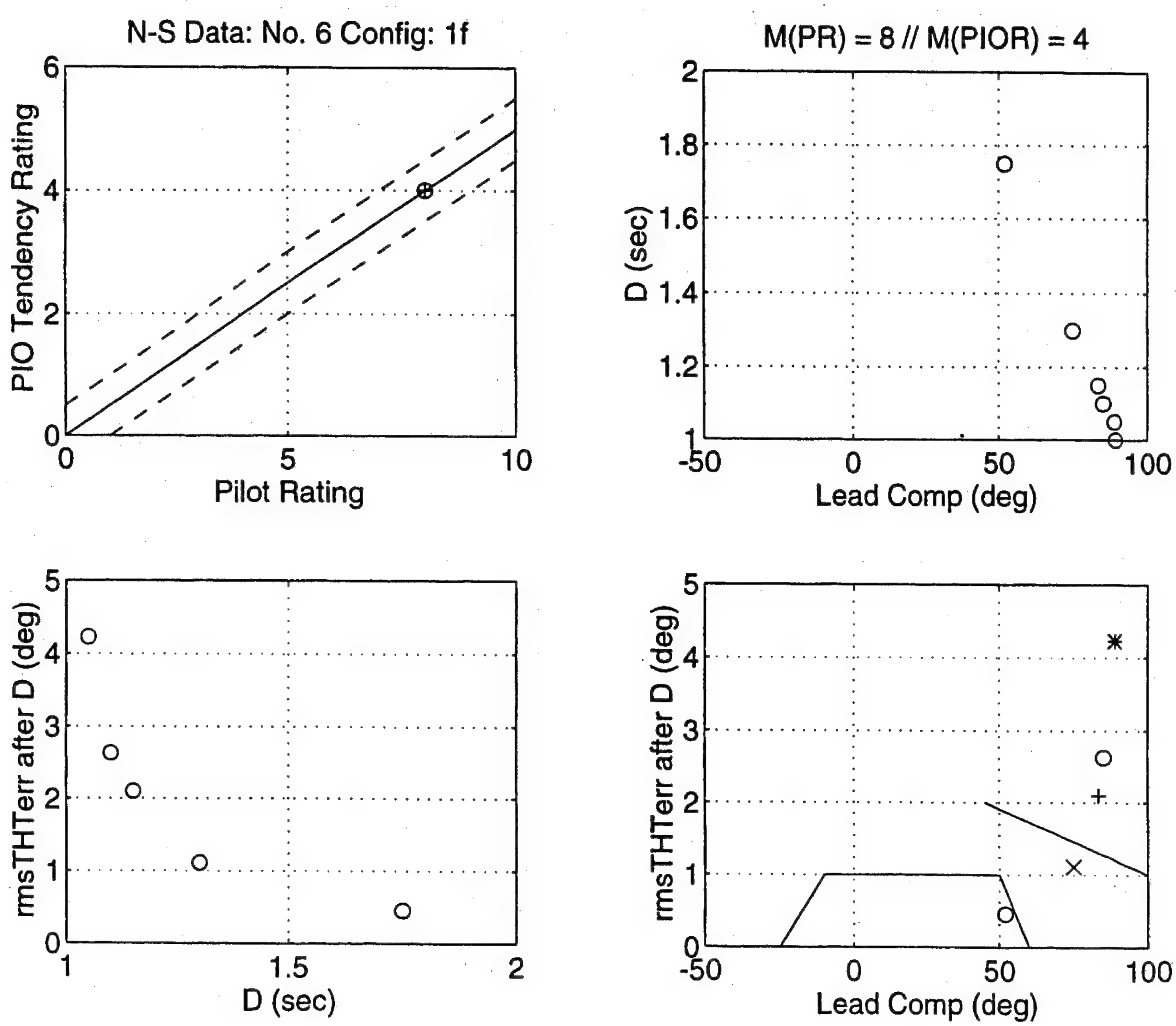

TIFS Data: No. 23 Config: 8-3-5
PIO Tendency Rating
Pilot Rating
M(PR) = 7 // M(PIOR) = 3
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

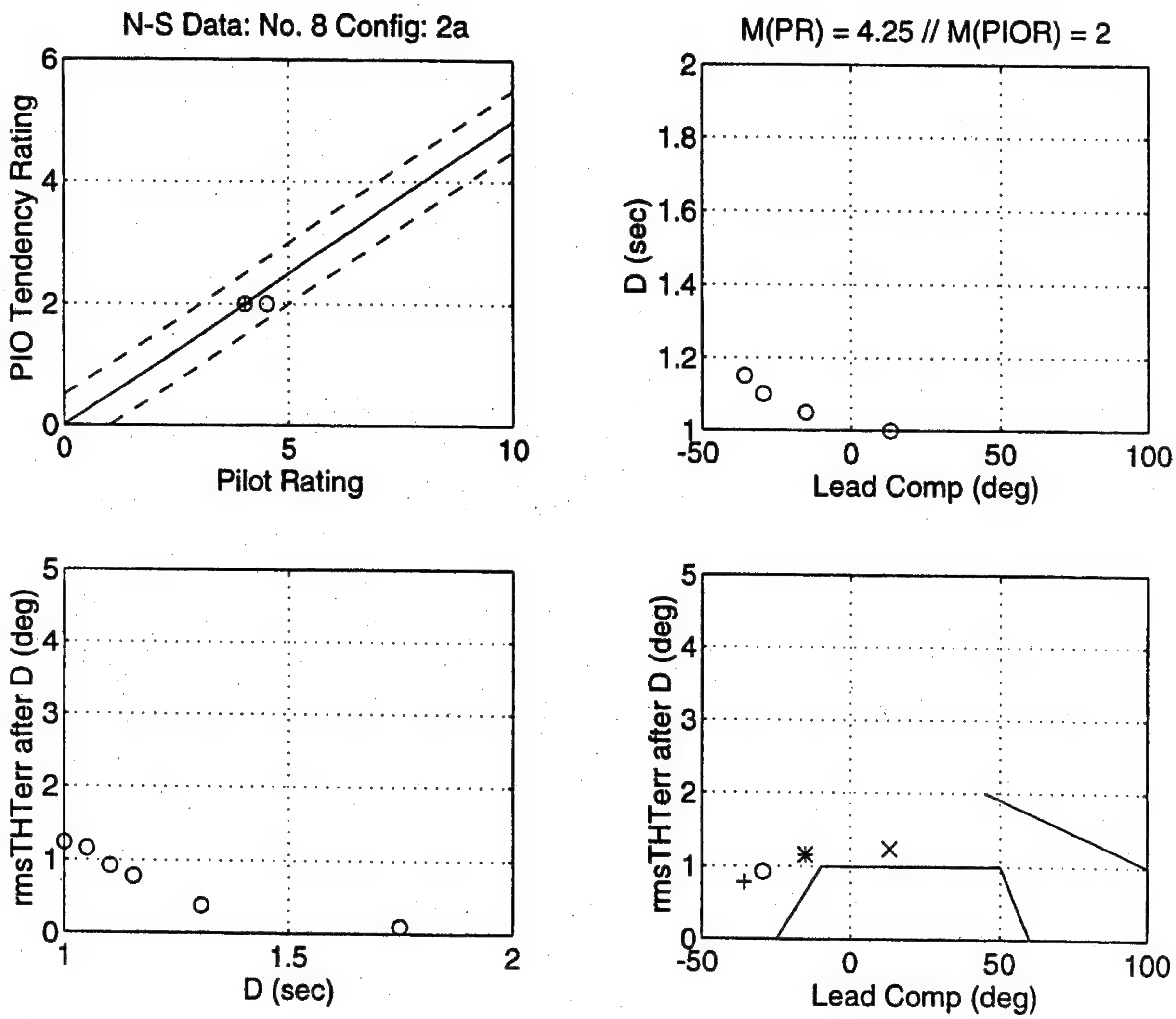

TIFS Data: No. 24 Config: 8-3-5-1
M(PR) = 3 // M(PIOR) = 1.25
PIO Tendency Rating
Pilot Rating
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

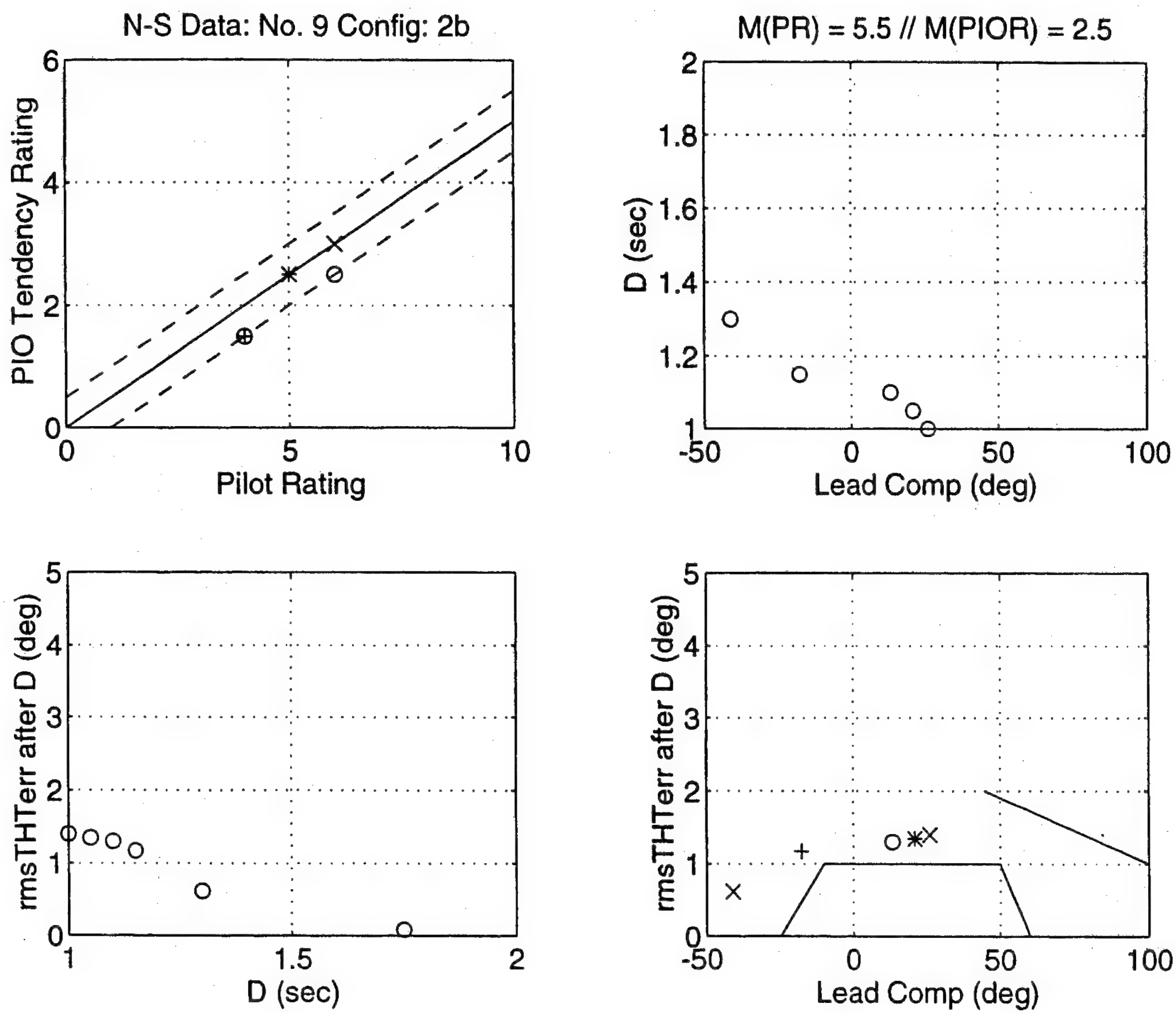

TIFS Data: No. 25 Config: 8-4-6
PIO Tendency Rating
Pilot Rating
M(PR) = 1 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

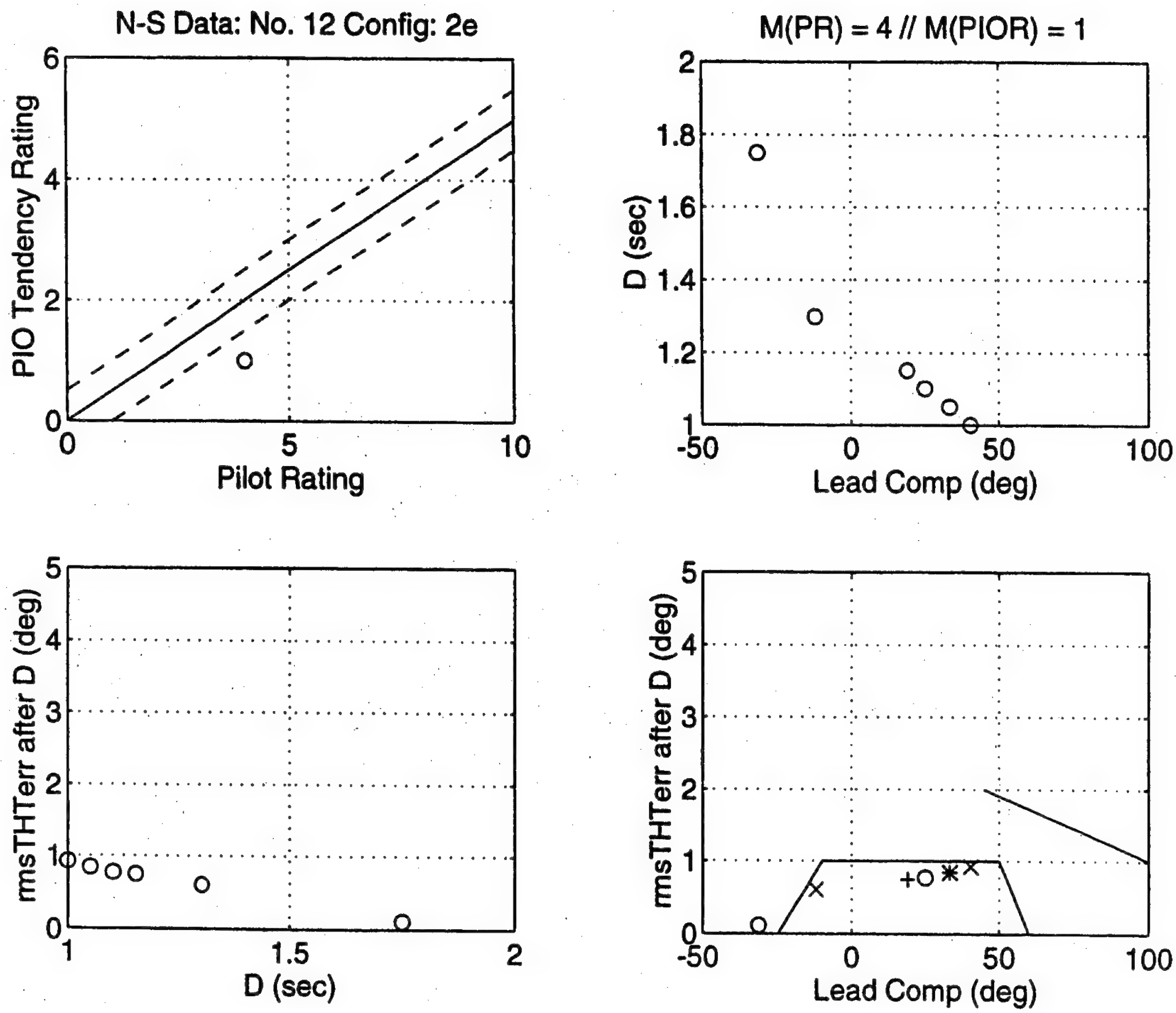

N-S Data: No. 1 Config: 1a
PIO Tendency Rating
Pilot Rating
M(PR) = 5 // M(PIOR) = 2
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


N-S Data: No. 4 Config: 1d
M(PR) = 4.25 // M(PIOR) = 2
PIO Tendency Rating
Pilot Rating
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

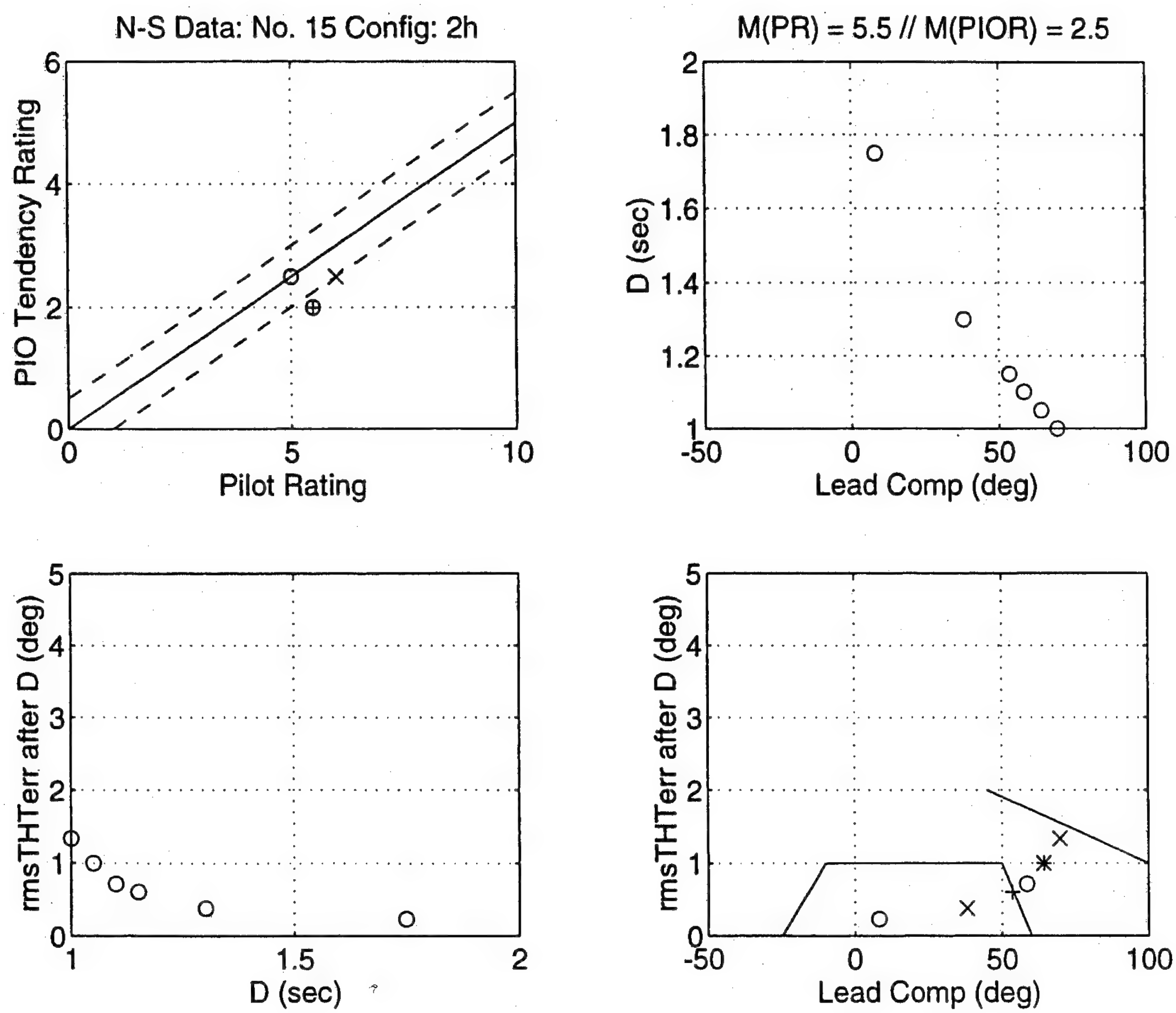

N-S Data: No. 6 Config: 1f
PIO Tendency Rating
Pilot Rating
M(PR) = 8 // M(PIOR) = 4
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


N-S Data: No. 8 Config: 2a
PIO Tendency Rating
Pilot Rating
M(PR) = 4.25 // M(PIOR) = 2
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

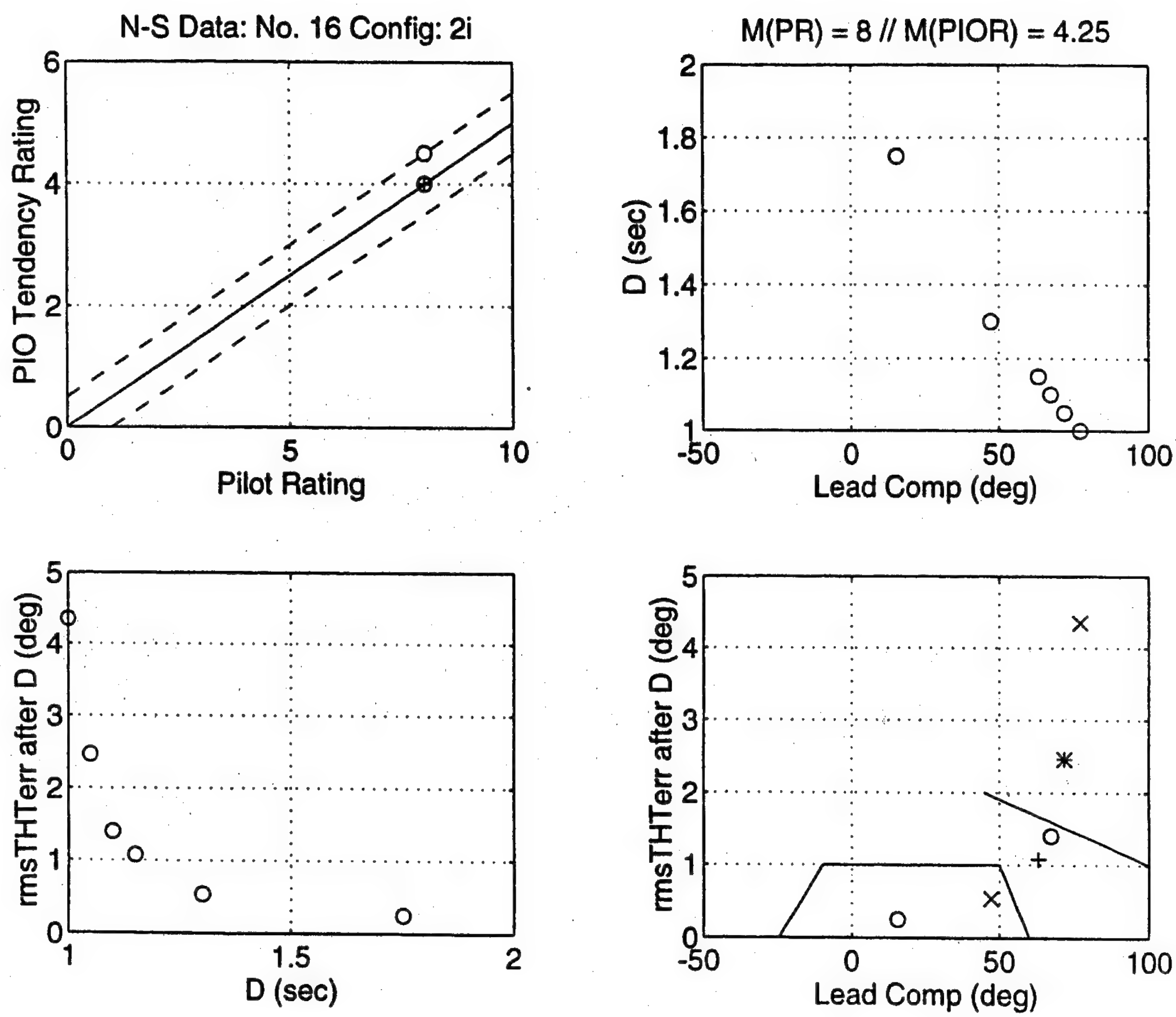

N-S Data: No. 9 Config: 2b
PIO Tendency Rating
Pilot Rating
M(PR) = 5.5 // M(PIOR) = 2.5
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

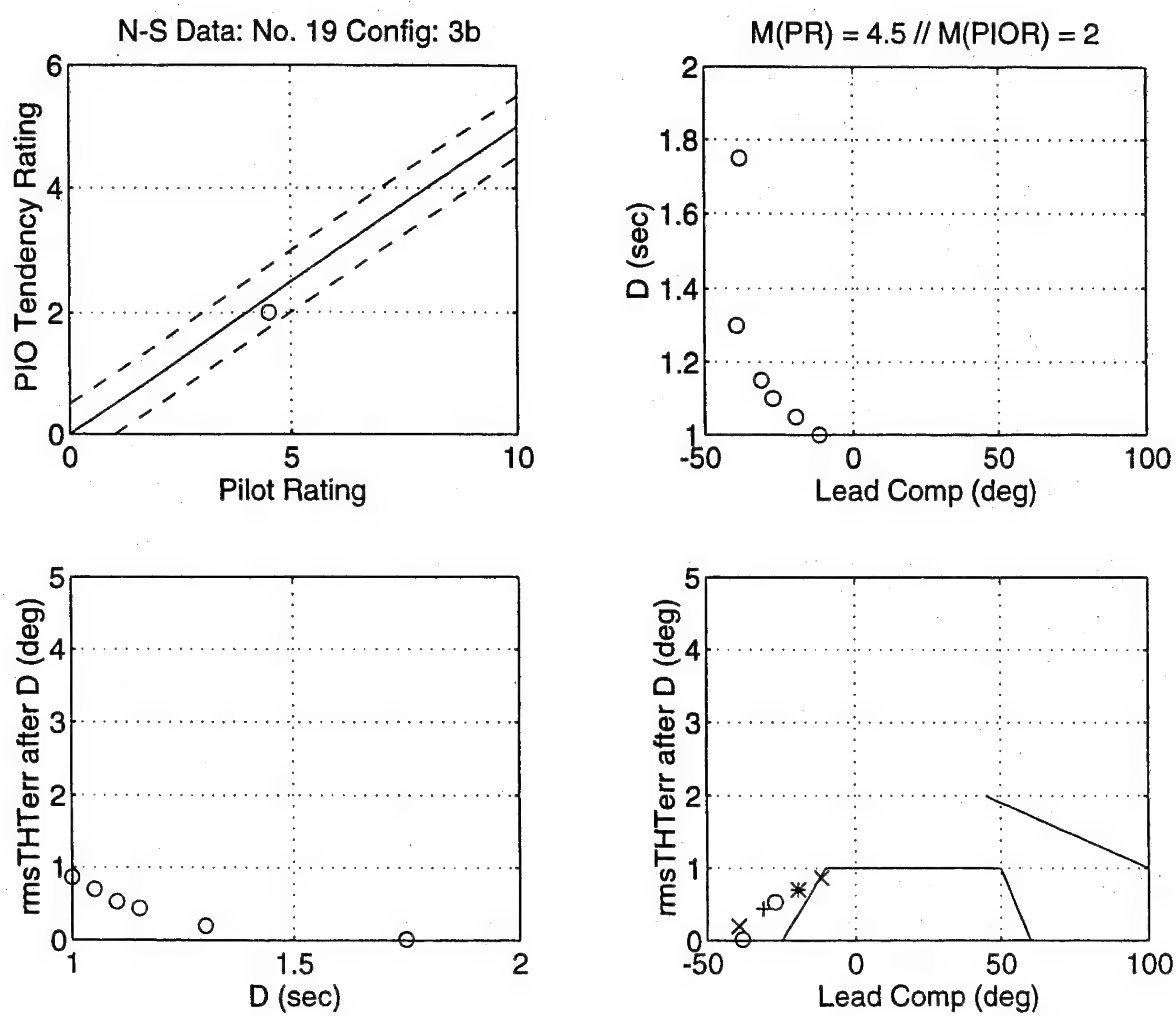


N-S Data: No. 12 Config: 2e
PIO Tendency Rating
Pilot Rating
M(PR) = 4 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
msTHTerr after D (deg)
D (sec)
msTHTerr after D (deg)
Lead Comp (deg)

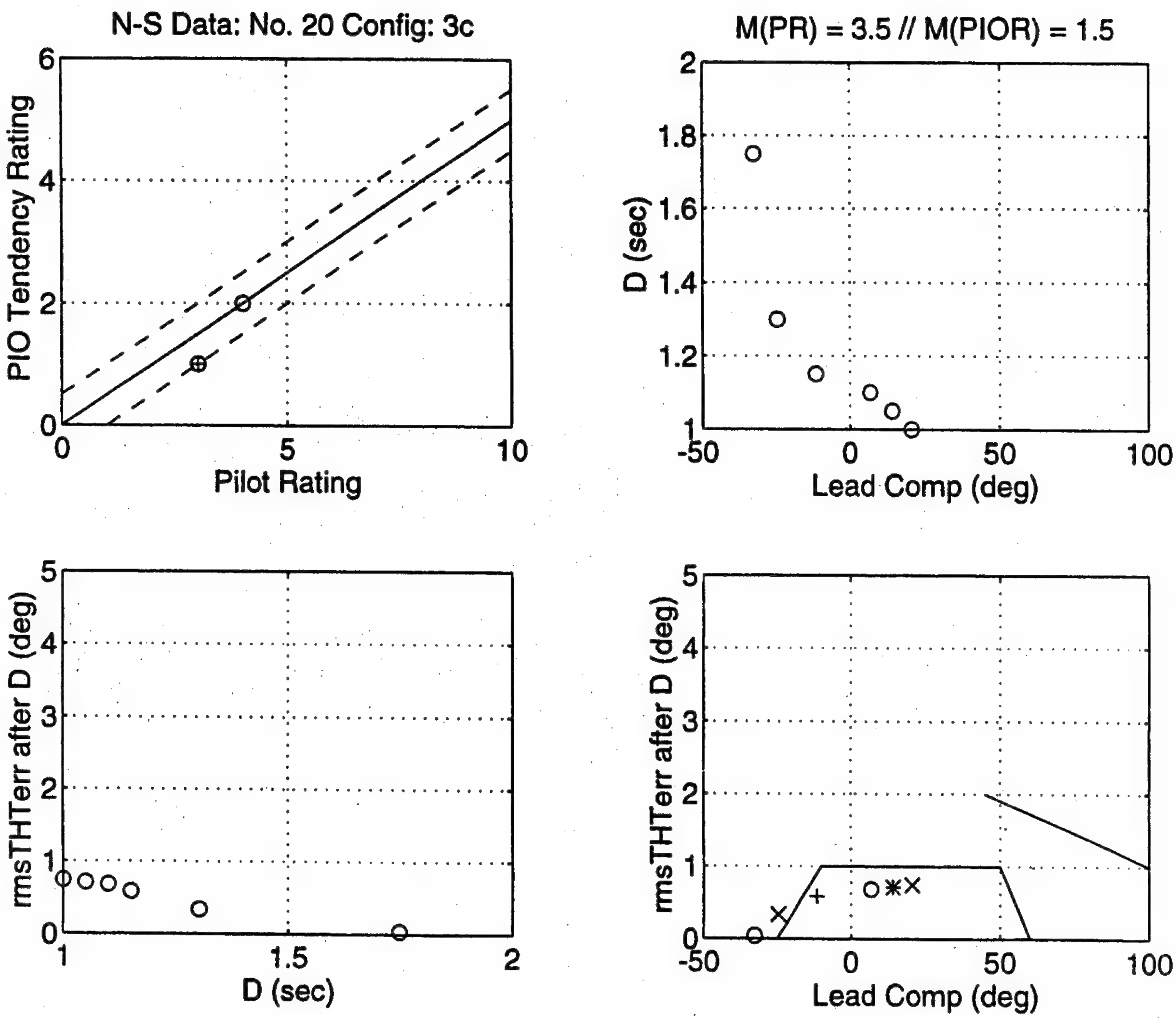


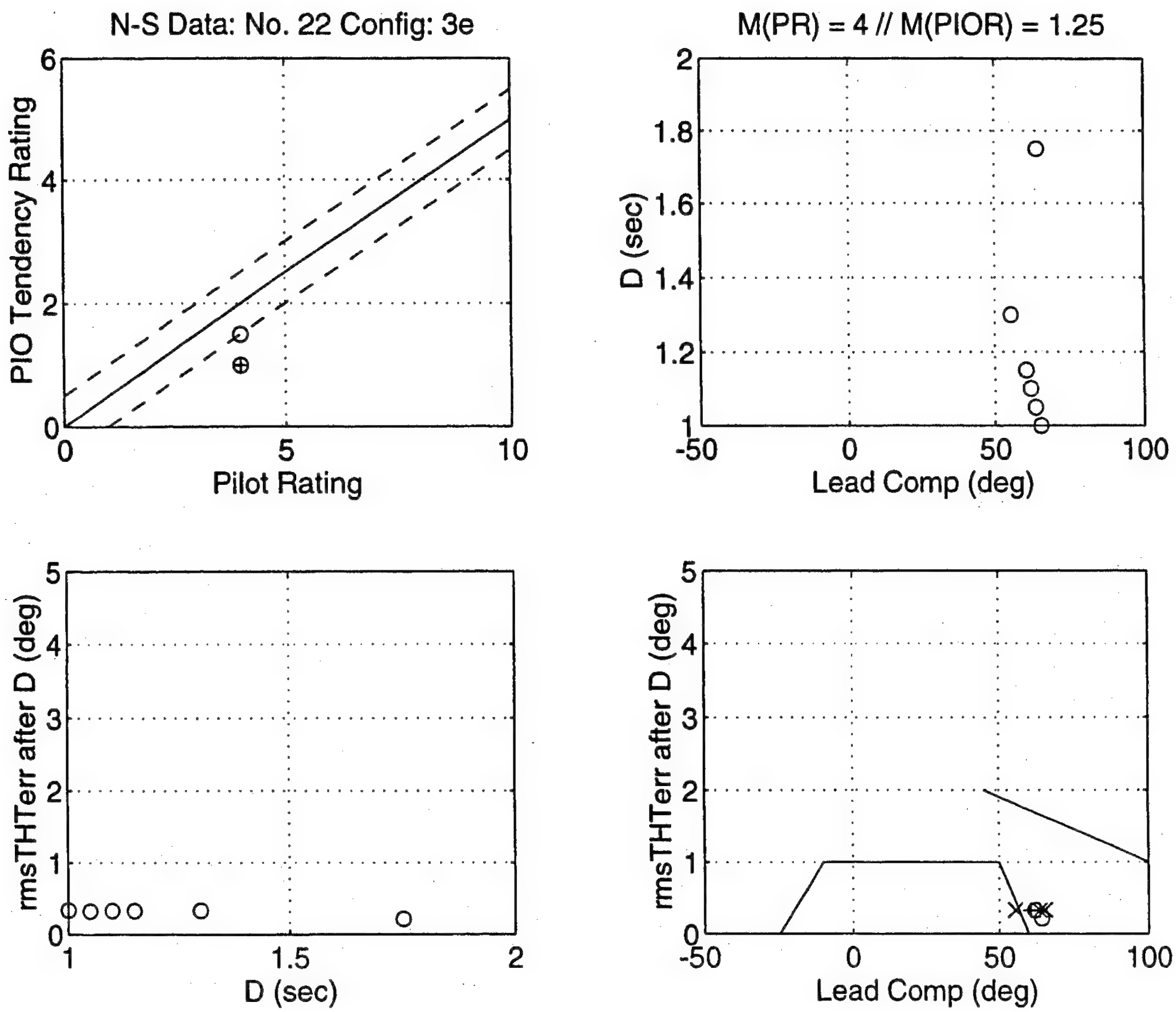
N-S Data: No. 15 Config: 2h
PIO Tendency Rating
Pilot Rating
M(PR) = 5.5 // M(PIOR) = 2.5
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


N-S Data: No. 16 Config: 2i
PIO Tendency Rating
Pilot Rating
M(PR) = 8 // M(PIOR) = 4.25
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

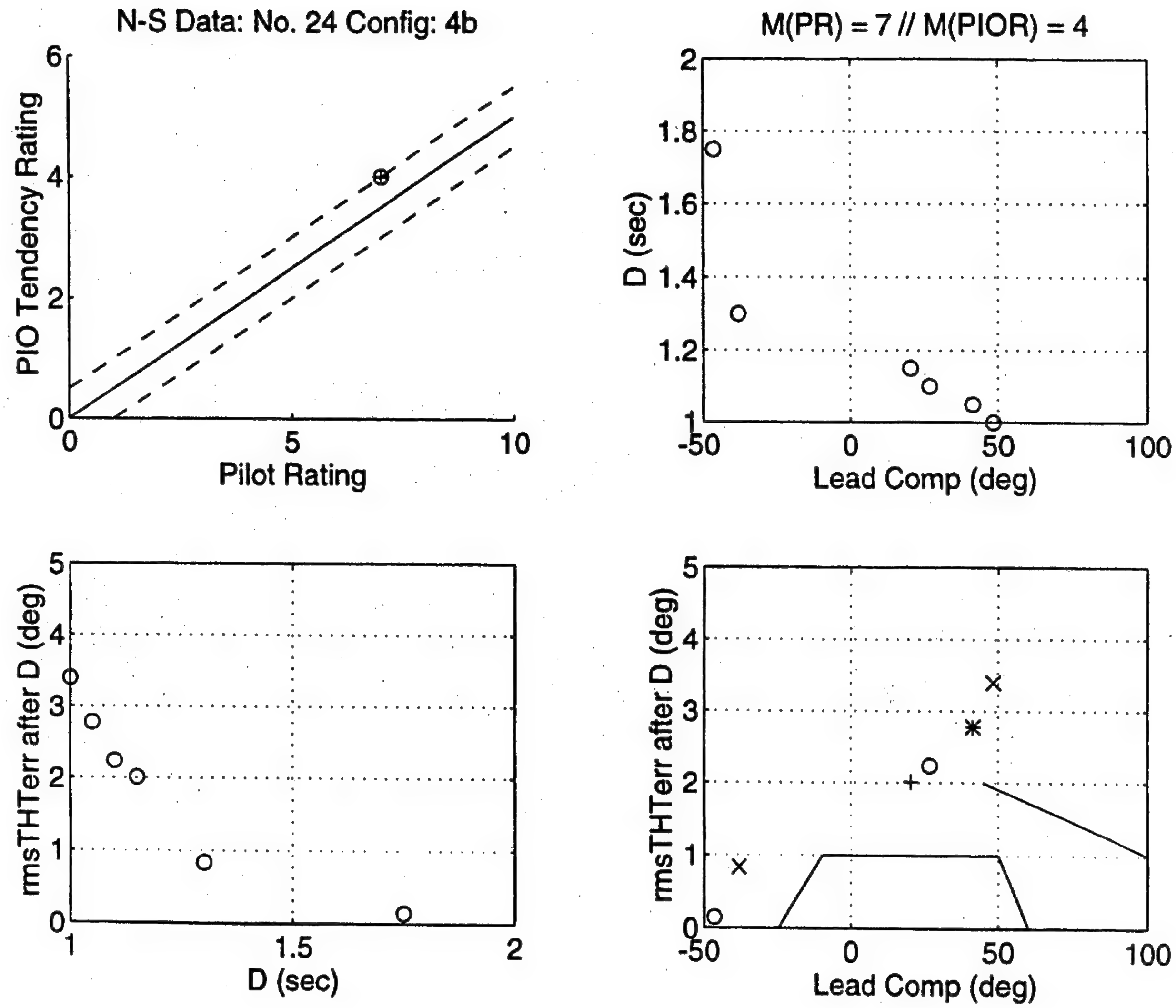


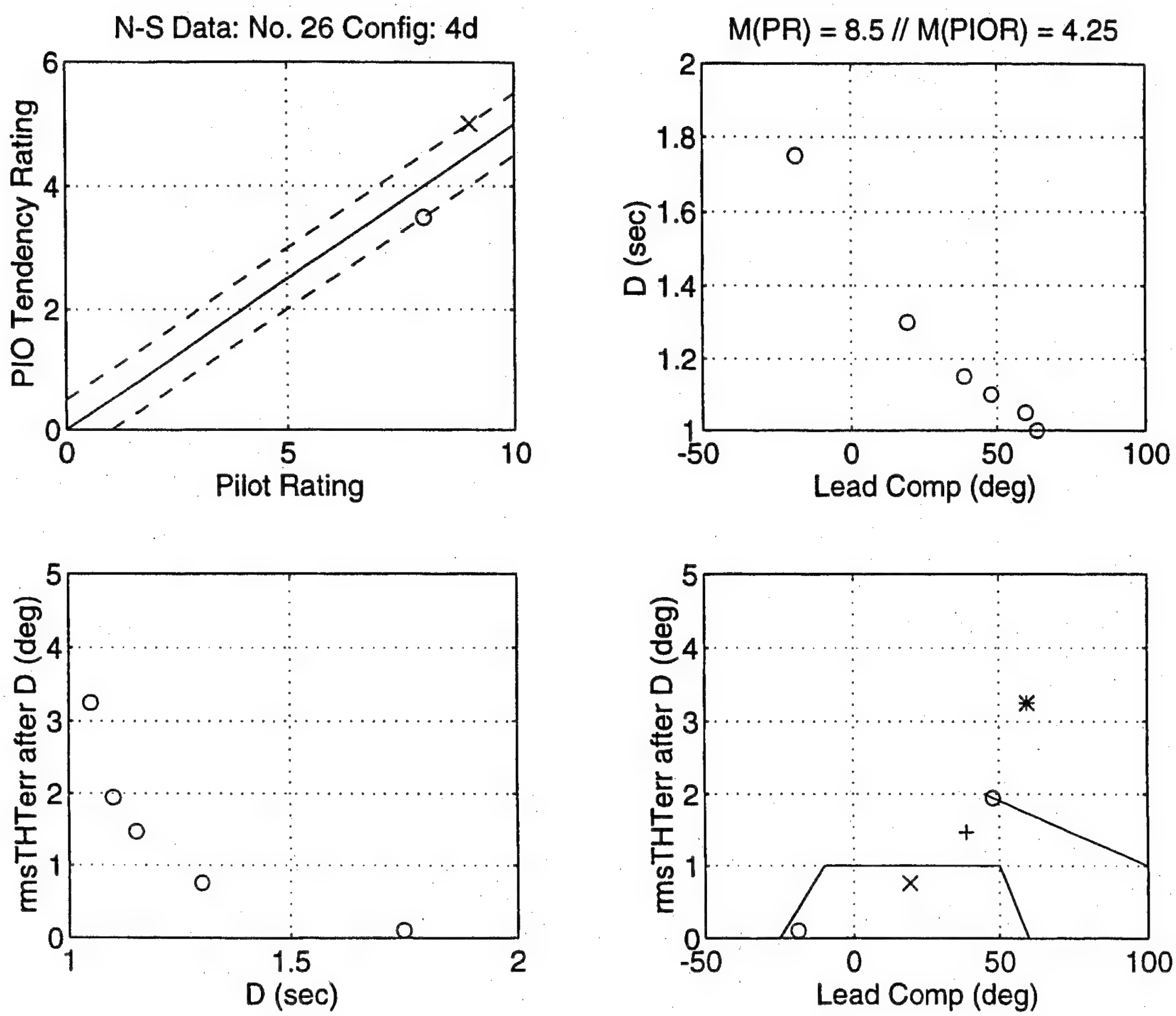
N-S Data: No. 19 Config: 3b
PIO Tendency Rating
Pilot Rating
M(PR) = 4.5 // M(PIOR) = 2
D (sec)
Lead Comp (deg)
msTHTerr after D (deg)
D (sec)
msTHTerr after D (deg)
Lead Comp (deg)

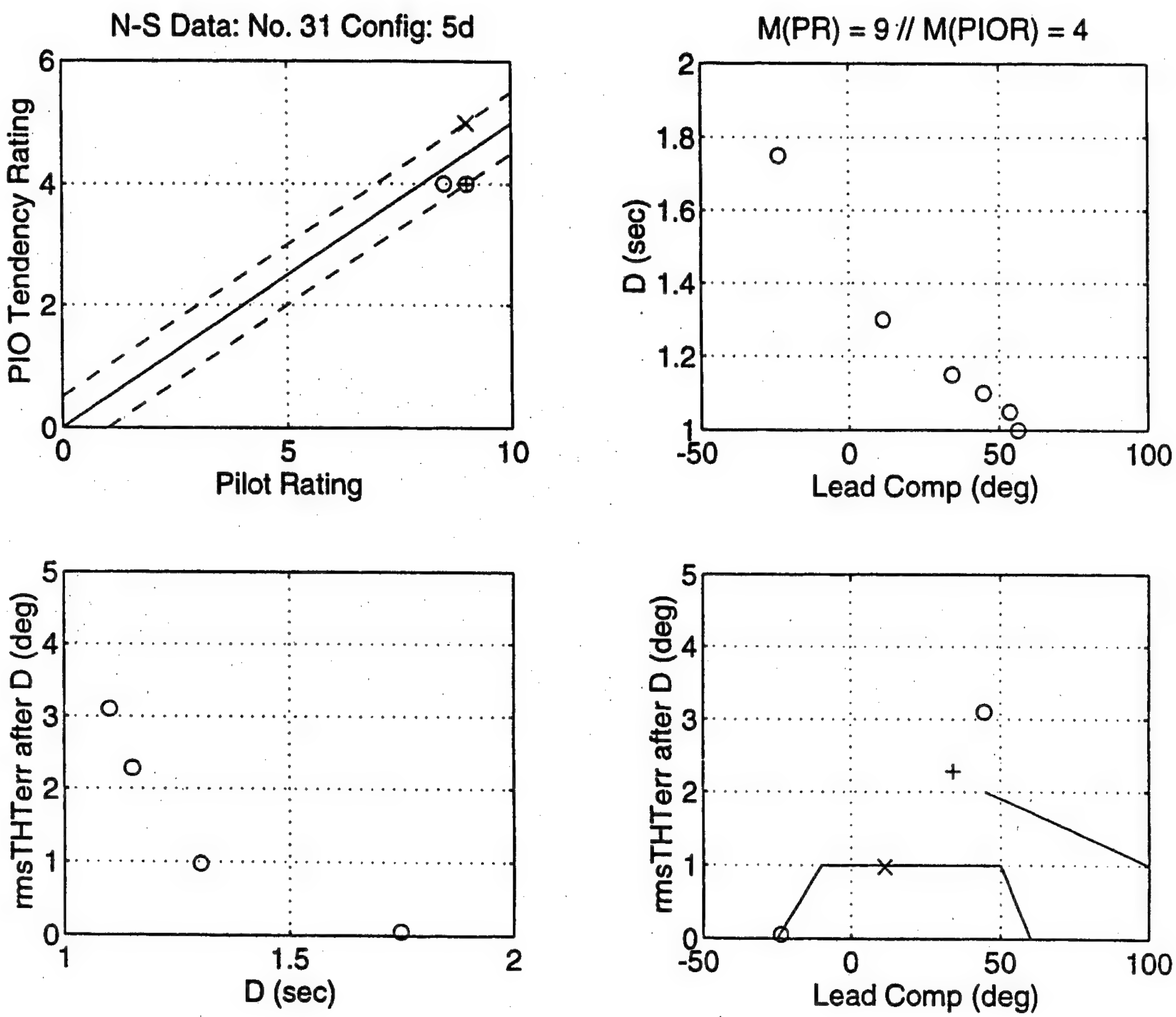

N-S Data: No. 20 Config: 3c
PIO Tendency Rating
Pilot Rating
M(PR) = 3.5 // M(PIOR) = 1.5
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

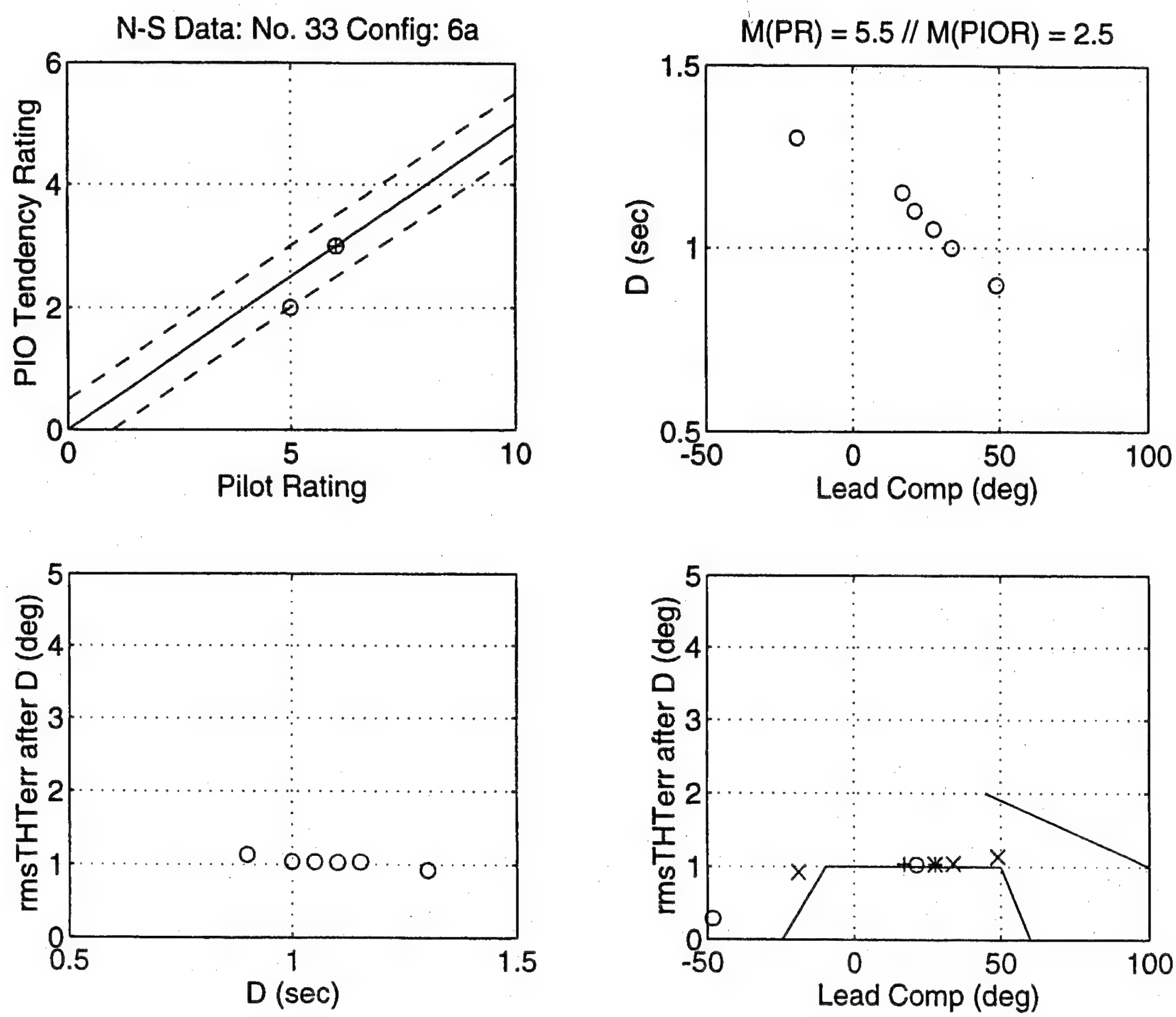


N-S Data: No. 22 Config: 3e
PIO Tendency Rating
Pilot Rating
M(PR) = 4 // M(PIOR) = 1.25
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

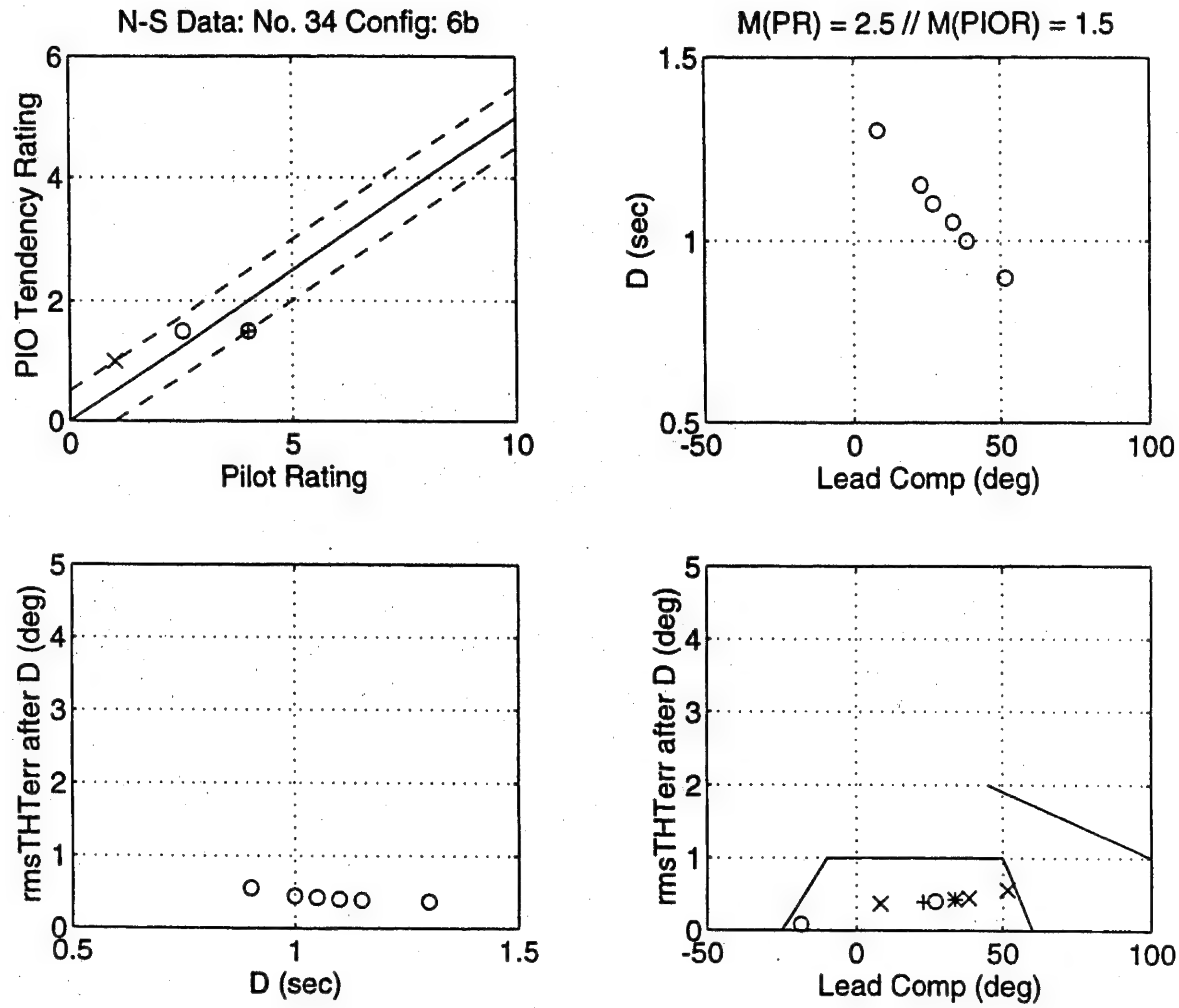

N-S Data: No. 24 Config: 4b
PIO Tendency Rating
Pilot Rating
M(PR) = 7 // M(PIOR) = 4
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


N-S Data: No. 26 Config: 4d
PIO Tendency Rating
Pilot Rating
0
2
4
6
0
5
10
M(PR) = 8.5 // M(PIOR) = 4.25
D (sec)
Lead Comp (deg)
1
1.2
1.4
1.6
1.8
2
-50
0
50
100
msTHTerr after D (deg)
D (sec)
0
1
2
3
4
5
1
1.5
2
msTHTerr after D (deg)
Lead Comp (deg)
0
1
2
3
4
5
-50
0
50
100

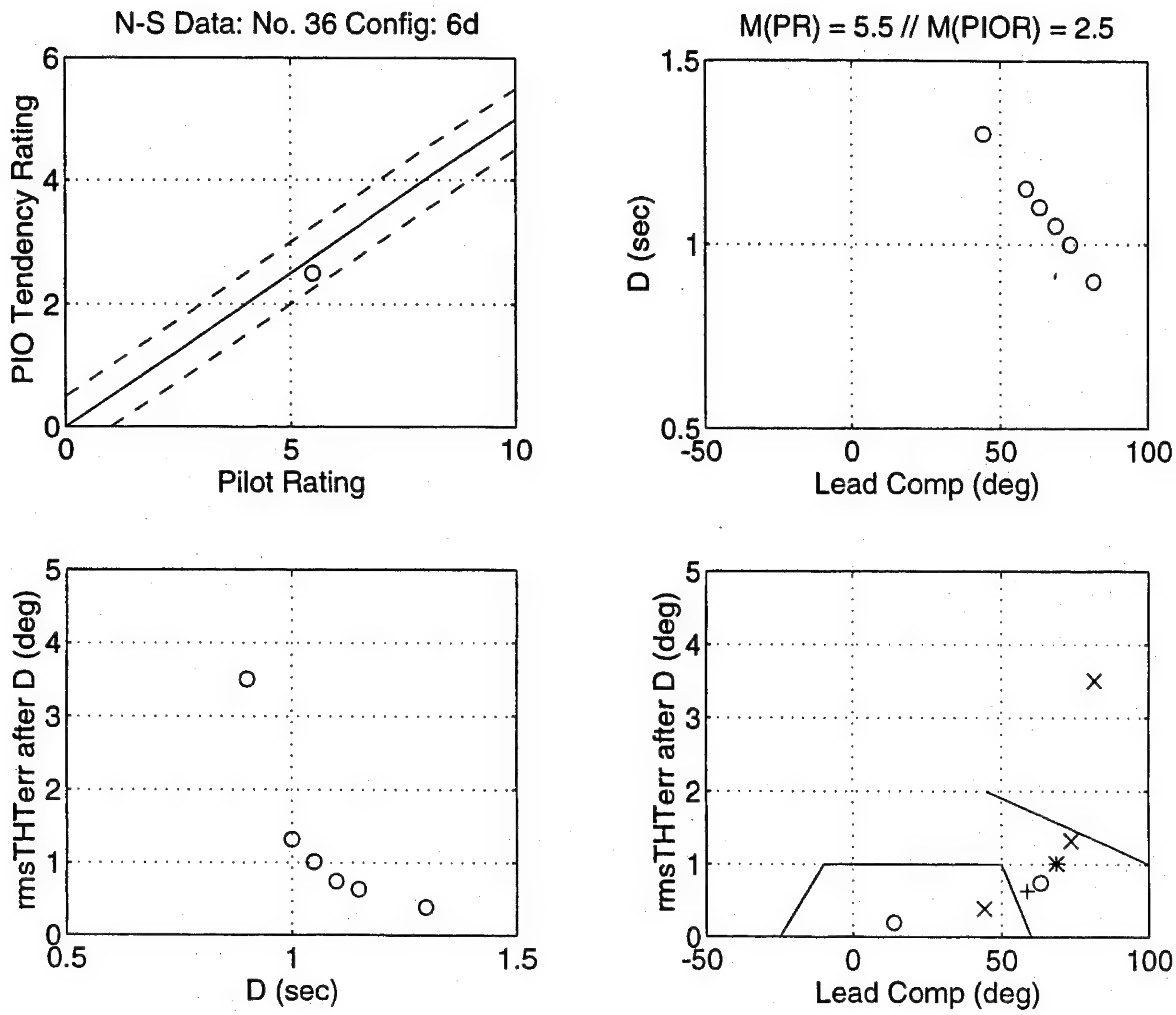

N-S Data: No. 31 Config: 5d
PIO Tendency Rating
Pilot Rating
M(PR) = 9 // M(PIOR) = 4
D (sec)
Lead Comp (deg)
msTHTerr after D (deg)
D (sec)
msTHTerr after D (deg)
Lead Comp (deg)



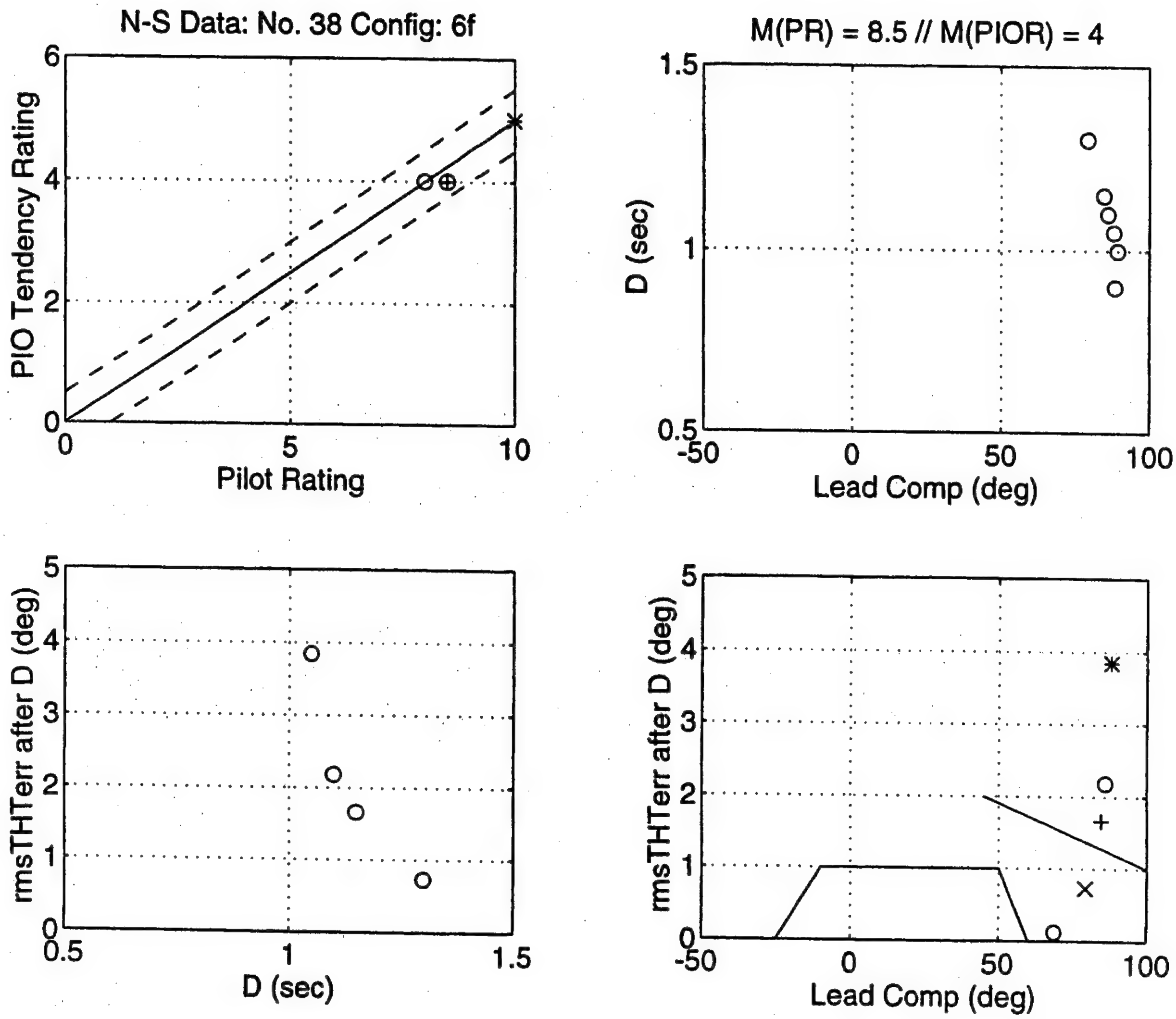
N-S Data: No. 33 Config: 6a
PIO Tendency Rating
Pilot Rating
M(PR) = 5.5 // M(PIOR) = 2.5
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)



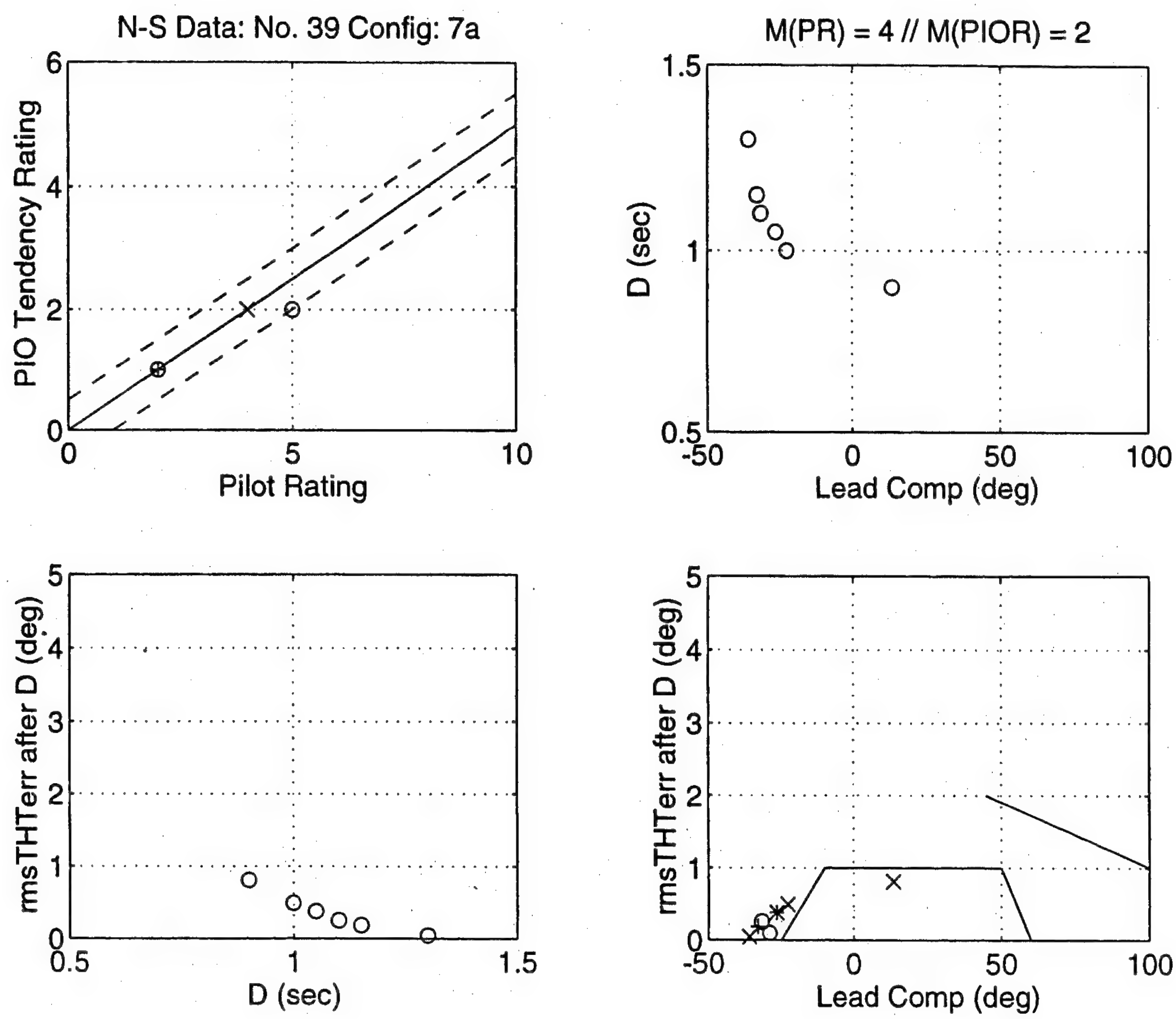
N-S Data: No. 34 Config: 6b
PIO Tendency Rating
Pilot Rating
M(PR) = 2.5 // M(PIOR) = 1.5
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

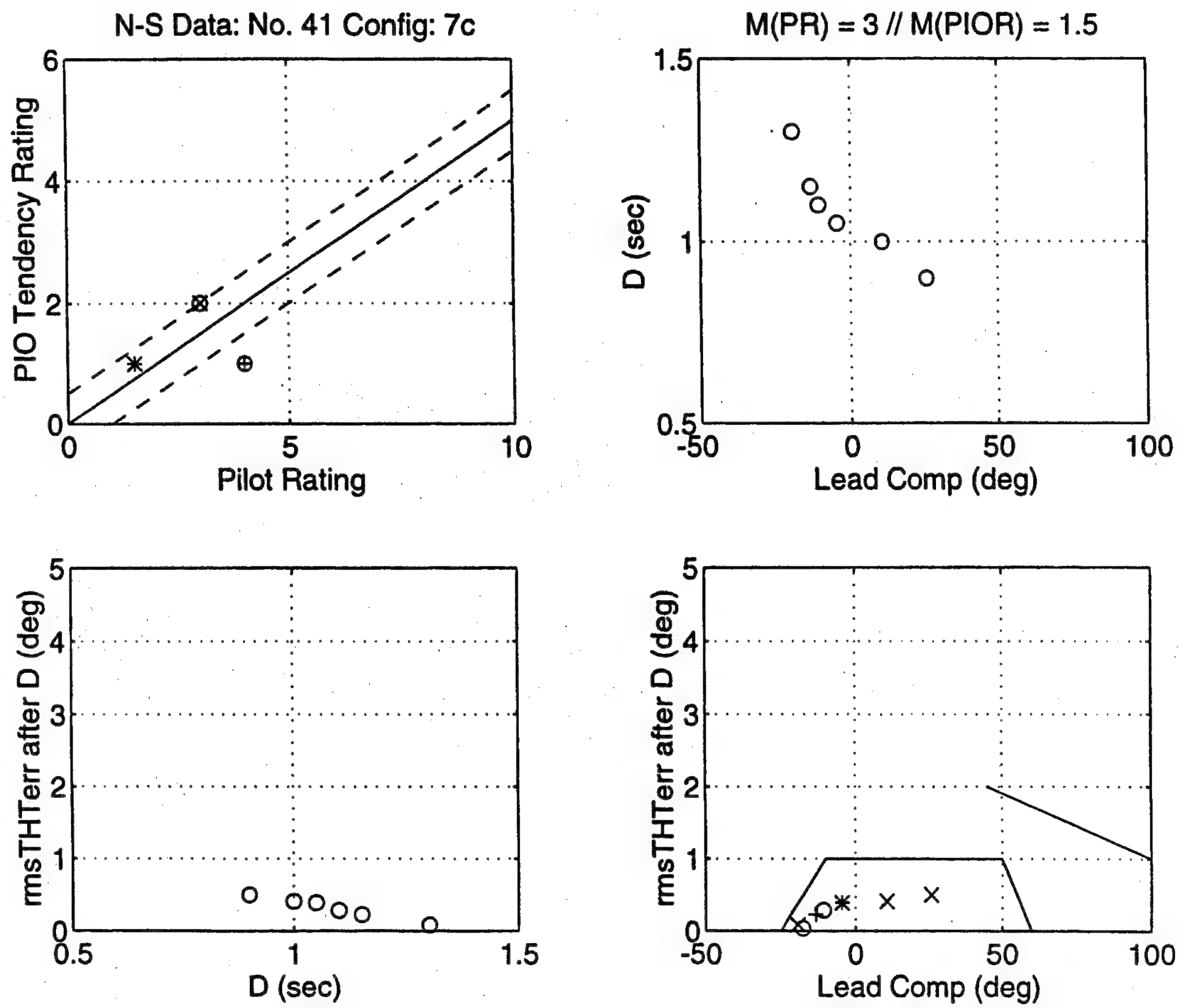


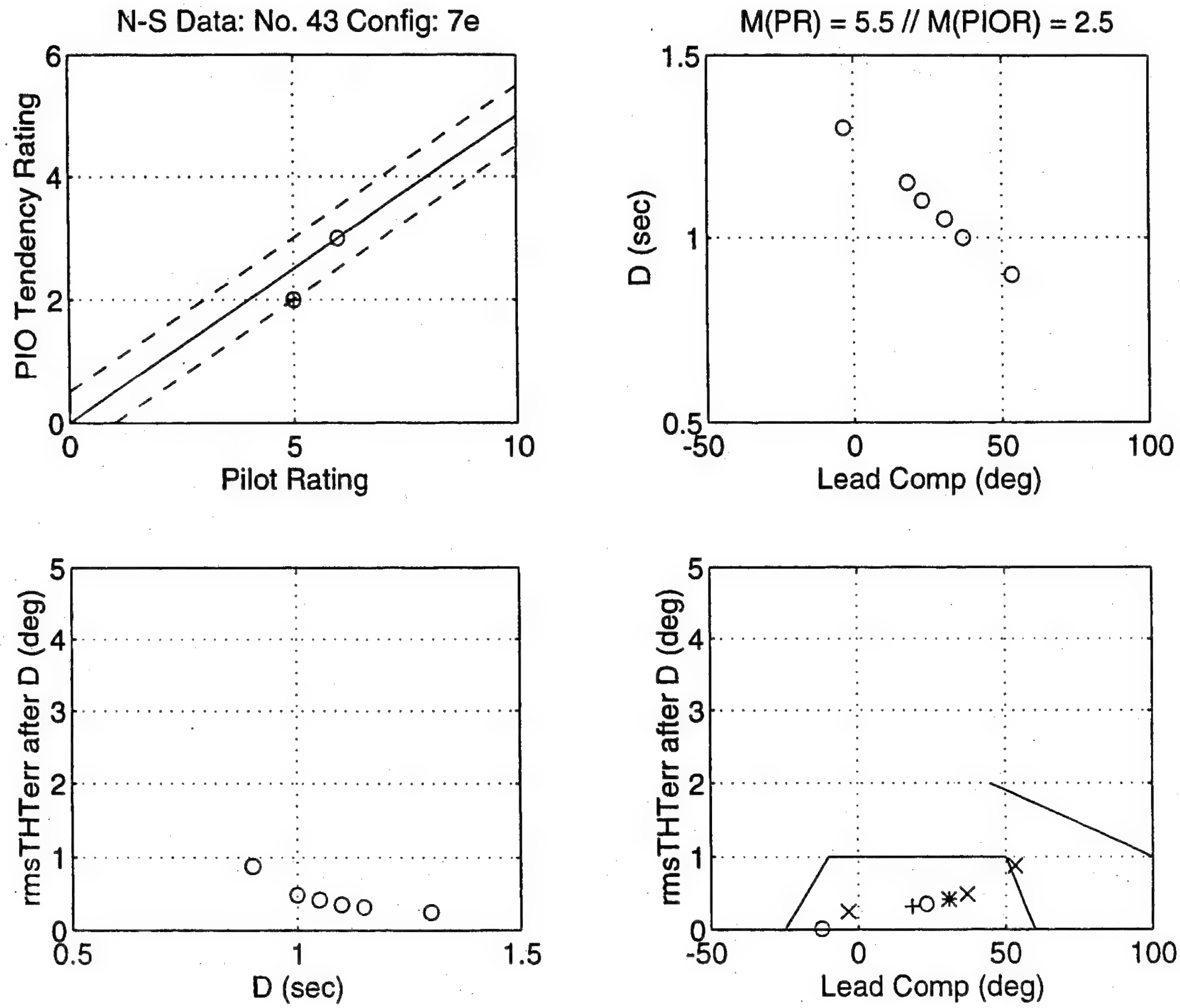
N-S Data: No. 36 Config: 6d
PIO Tendency Rating
Pilot Rating
0
2
4
6
0
5
10
M(PR) = 5.5 // M(PIOR) = 2.5
D (sec)
Lead Comp (deg)
0.5
1
1.5
-50
0
50
100
rmsTHTerr after D (deg)
D (sec)
0
1
2
3
4
5
0.5
1
1.5
rmsTHTerr after D (deg)
Lead Comp (deg)
0
1
2
3
4
5
-50
0
50
100



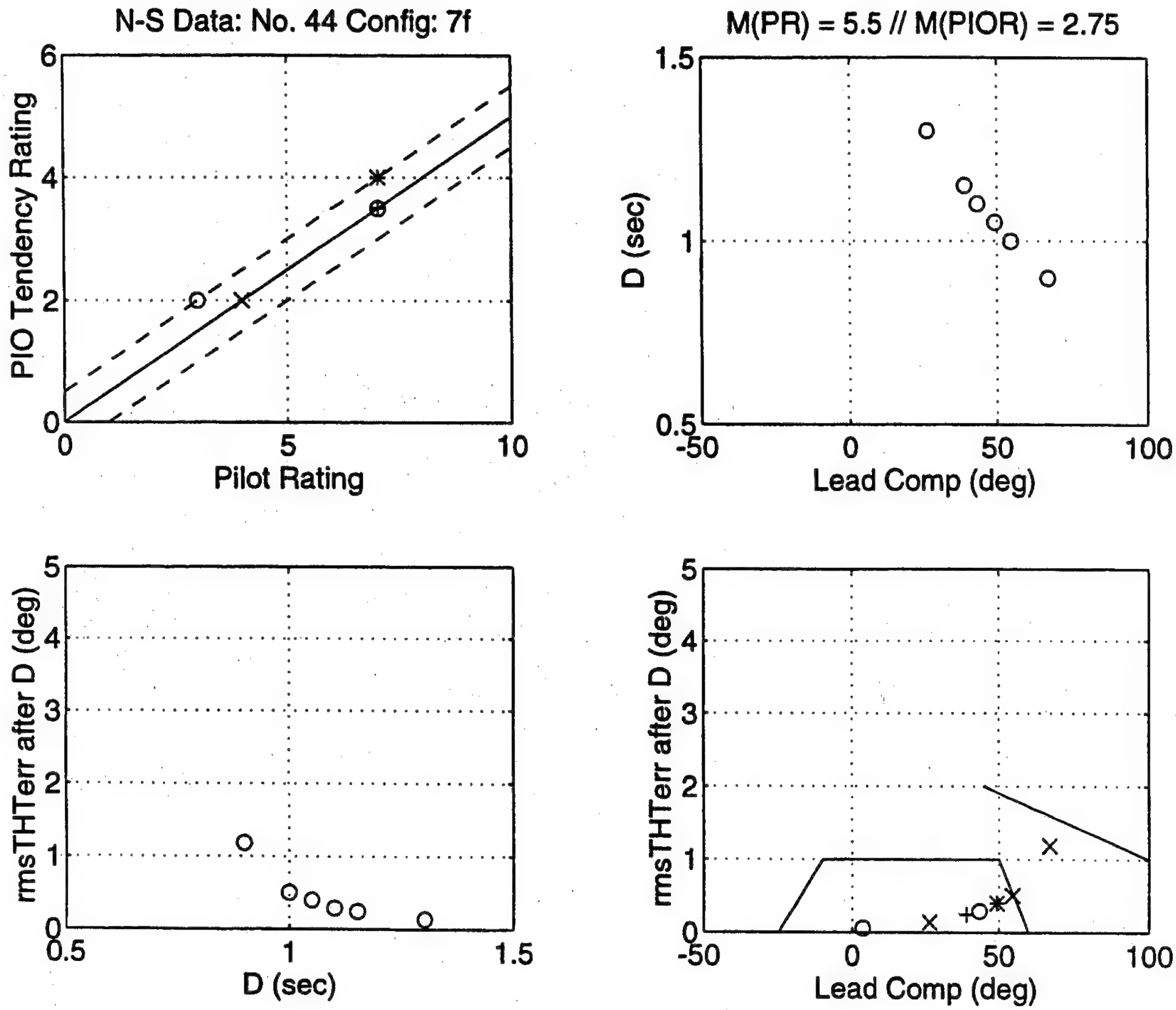
N-S Data: No. 38 Config: 6f
PIO Tendency Rating
Pilot Rating
0
2
4
6
5
10
M(PR) = 8.5 // M(PIOR) = 4
D (sec)
Lead Comp (deg)
1.5
1
0.5
-50
0
50
100
rmsTHTerr after D (deg)
D (sec)
0.5
1
1.5
1
2
3
4
5
rmsTHTerr after D (deg)
Lead Comp (deg)

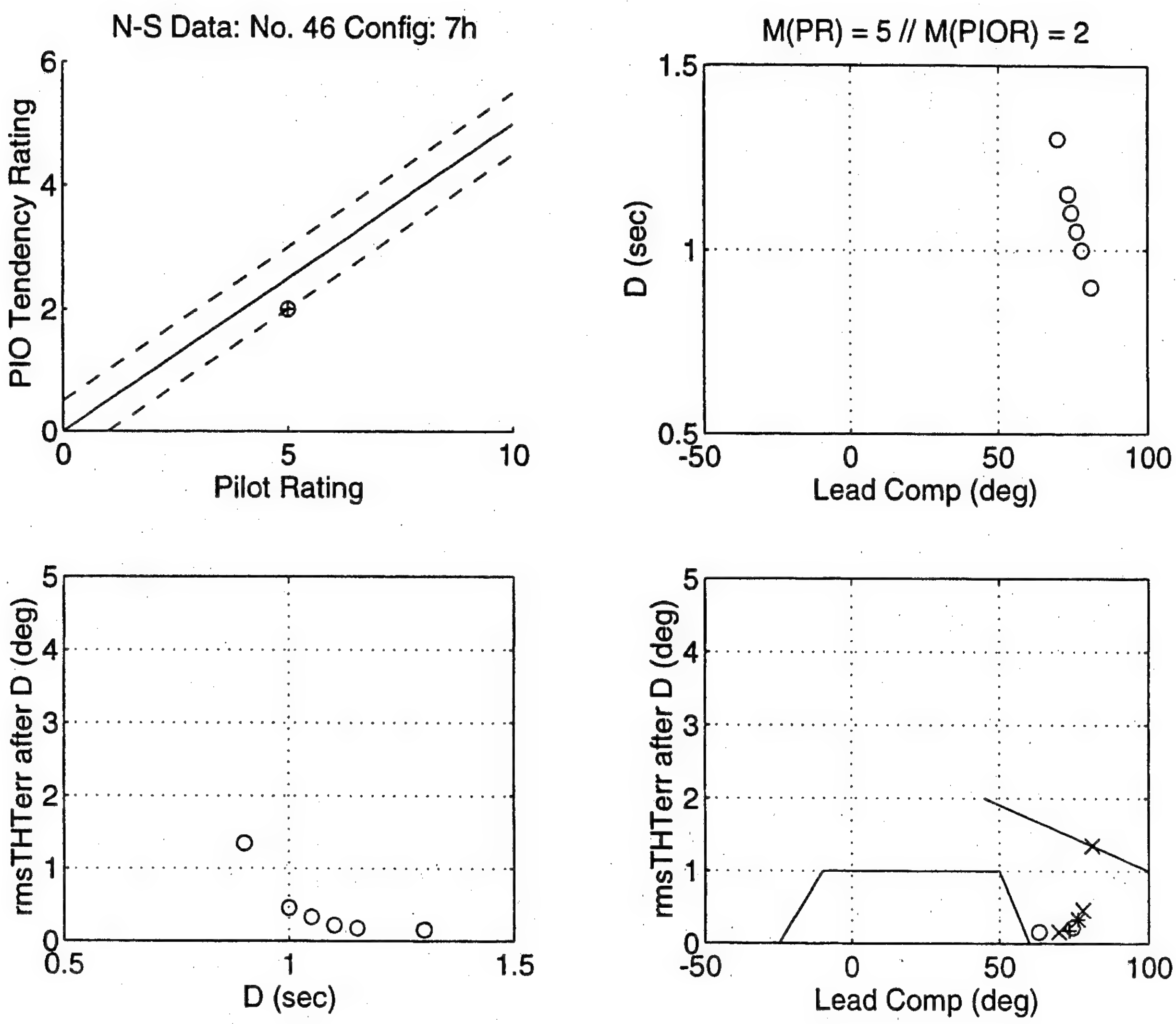

N-S Data: No. 39 Config: 7a
PIO Tendency Rating
Pilot Rating
M(PR) = 4 // M(PIOR) = 2
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


N-S Data: No. 41 Config: 7c
PIO Tendency Rating
Pilot Rating
0
2
4
6
0
5
10
M(PR) = 3 // M(PIOR) = 1.5
D (sec)
Lead Comp (deg)
0.5
1
1.5
-50
0
50
100
rmsTHTerr after D (deg)
D (sec)
0
1
2
3
4
5
0.5
1
1.5
rmsTHTerr after D (deg)
Lead Comp (deg)
-50
0
50
100

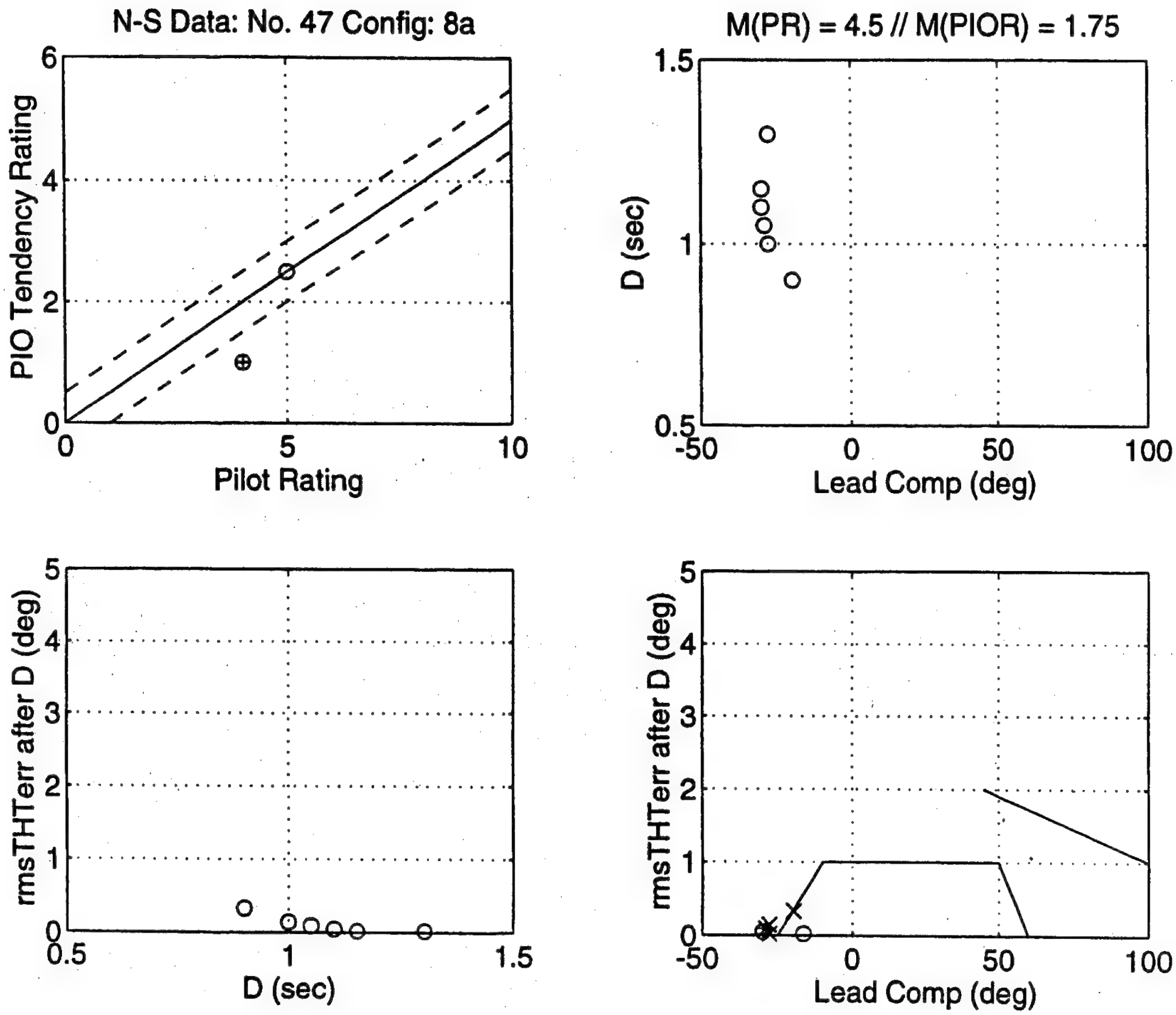


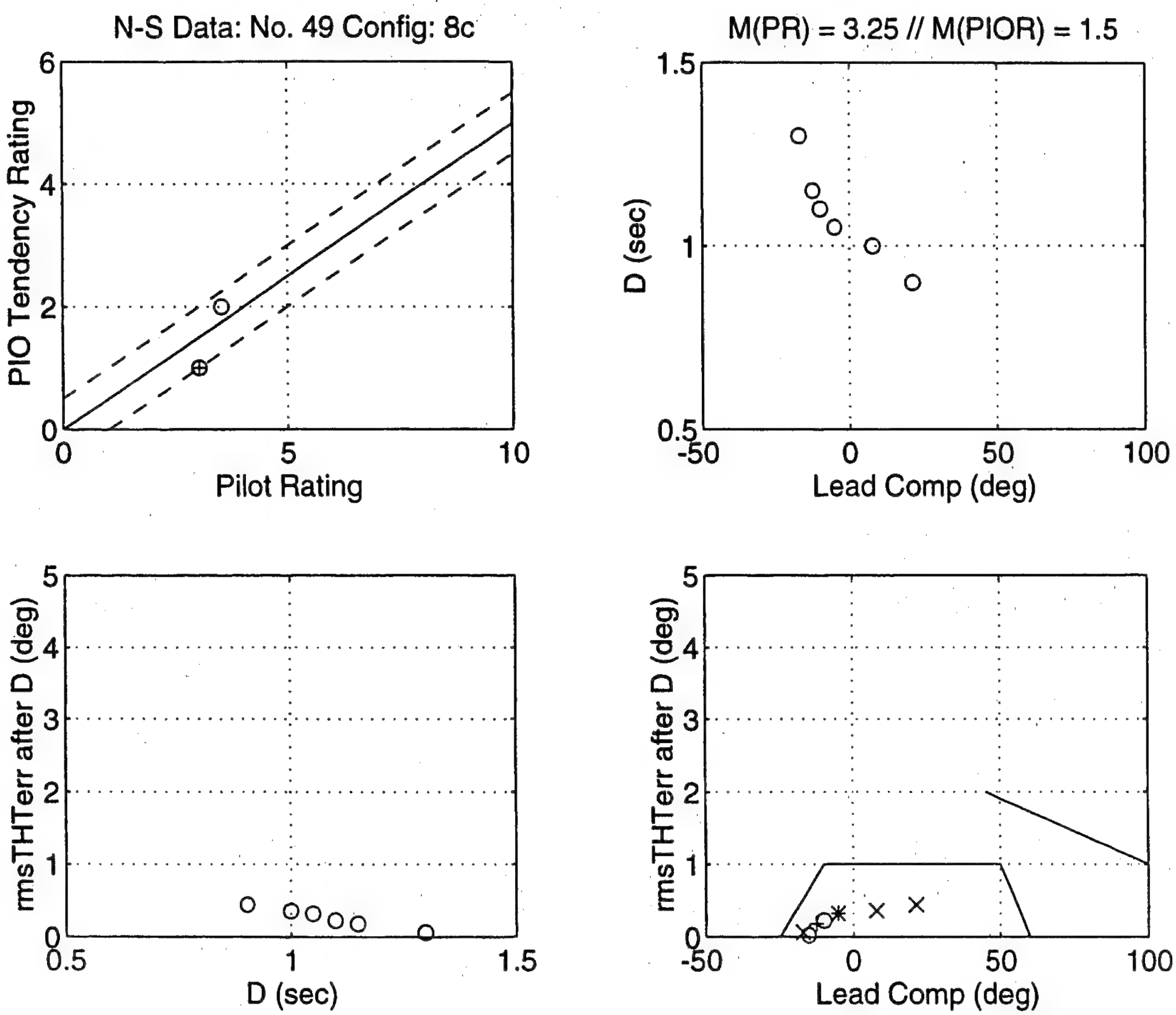
N-S Data: No. 43 Config: 7e
PIO Tendency Rating
Pilot Rating
M(PR) = 5.5 // M(PIOR) = 2.5
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


N-S Data: No. 44 Config: 7f
PIO Tendency Rating
Pilot Rating
M(PR) = 5.5 // M(PIOR) = 2.75
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

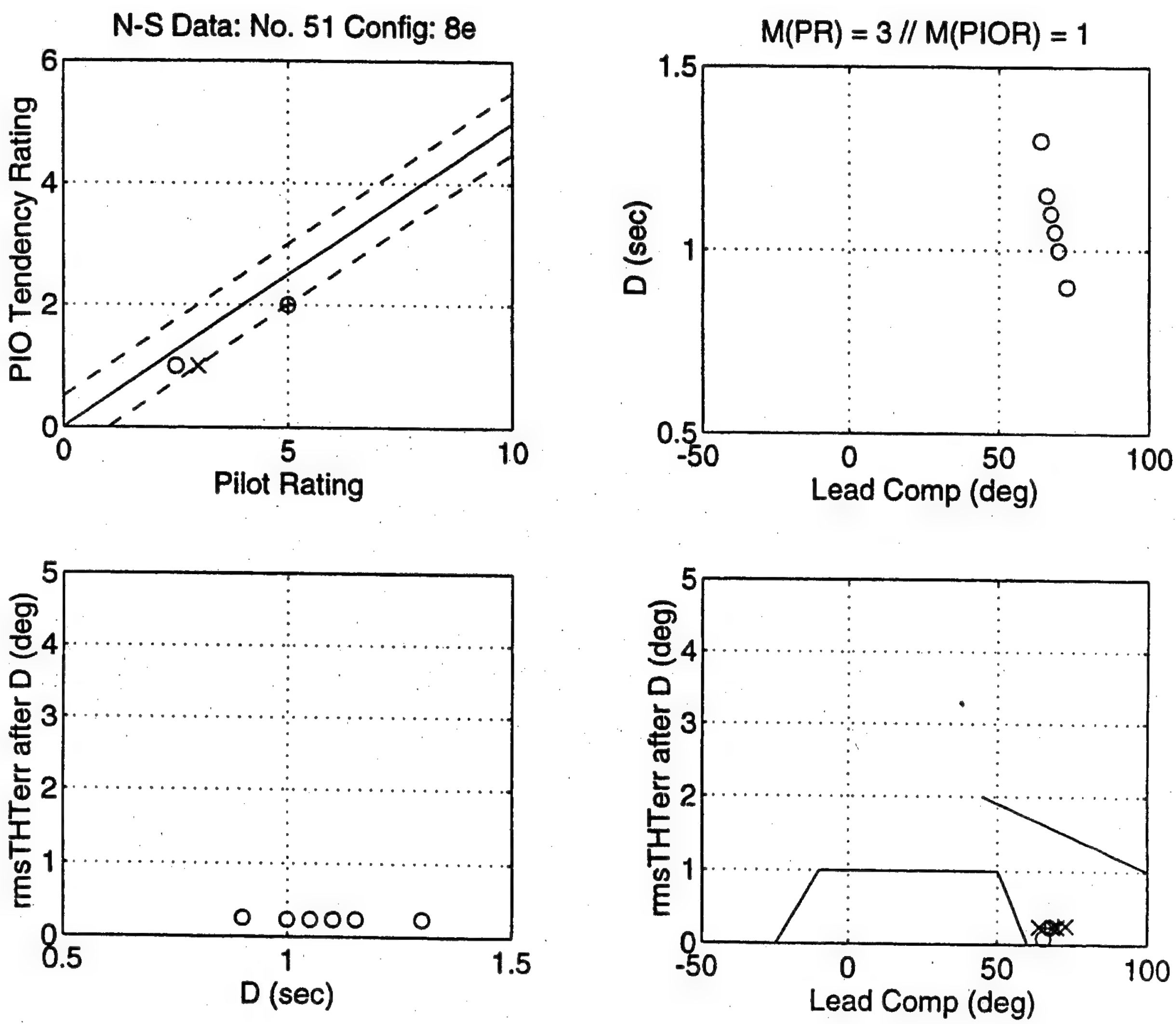


N-S Data: No. 46 Config: 7h
M(PR) = 5 // M(PIOR) = 2
PIO Tendency Rating
Pilot Rating
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)


N-S Data: No. 47 Config: 8a
PIO Tendency Rating
Pilot Rating
M(PR) = 4.5 // M(PIOR) = 1.75
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)



N-S Data: No. 49 Config: 8c
PIO Tendency Rating
Pilot Rating
0
2
4
6
0
5
10
M(PR) = 3.25 // M(PIOR) = 1.5
D (sec)
Lead Comp (deg)
0.5
1
1.5
-50
0
50
100
rmsTHTerr after D (deg)
D (sec)
0
1
2
3
4
5
0.5
1
1.5
rmsTHTerr after D (deg)
Lead Comp (deg)
-50
0
50
100



N-S Data: No. 51 Config: 8e
PIO Tendency Rating
Pilot Rating
M(PR) = 3 // M(PIOR) = 1
D (sec)
Lead Comp (deg)
rmsTHTerr after D (deg)
D (sec)
rmsTHTerr after D (deg)
Lead Comp (deg)

Appendix E
Data Base Listings

In the following tables, the configurations and pilot ratings are listed for the three flying qualities data bases. These tables are published to document the median pilot ratings and median PIO ratings that were used in the correlations produced in the main text.

The pilot ratings were extracted from the original reports. Evaluations that were discarded or discredited by the reference authors were not used in computation of median ratings.

In Table E-I, the evaluation summary for the Neal-Smith data base (Reference 8) is given.

In Table E-II, the evaluation summary for the LAHOS data base (Reference 17) is given. Only the overall ratings - not the approach only ratings - are used in the analyzes.

In Table E-II, the evaluation summary for the TIFS Pitch Rate program (Reference 18) is given. Only the overall ratings - not the approach only ratings - are used in the analyzes.

For the Neal-Smith data base and the LAHOS data base, PIO tendencies were rated according to the PIO Tendency Classification scale shown in Figure E-1. In Reference 18, this scale was taken essentially verbatim but broken out into a decision tree format, analogous to the Cooper-Harper rating scale, to make the assignment of PIO tendency ratings easier for the pilots and to provide more repeatable, reliable data. In this report, PIO tendencies are considered to be prevalent if a PIO rating of greater than 3 was given.

DESCRIPTION	NUMERICAL RATING
NO TENDENCY FOR PILOT TO INDUCE UNDESIRABLE MOTIONS.	1
UNDESIRABLE MOTIONS TEND TO OCCUR WHEN PILOT INITIATES ABRUPT NAMEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BY PILOT TECHNIQUE.	2
UNDESIRABLE MOTIONS EASILY INDUCED WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BUT ONLY AT SACRIFICE TO TASK PERFORMANCE OR THROUGH CONSIDERABLE PILOT ATTENTION AND EFFORT.	3
OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST REDUCE GAIN OR ABANDON TASK TO RECOVER.	4
DIVERGENT OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST OPEN LOOP BY RELEASING OR FREEZING THE STICK.	5
DISTURBANCE OR NORMAL PILOT CONTROL MAY CAUSE DIVERGENT OSCILLATION. PILOT MUST OPEN CONTROL LOOP BY RELEASEING OR FREEZING THE STICK.	6

Reference: DiFrance, D.A.: In-Flight Investigation of the Effects of Higher-Order System Dynamics on Longitudinal Handling Qualities, AFFDL-TR-69-3, April 1969.

reb-PIO: Task Plan/Proposal: PD Tendency Rating Scale

Figure E-1: PIO Tendency Classification Scale

Table E-I
Neal-Smith Evaluation Data Summary

No.	Configuration	Median PR	Median PIOR	Pilot M, 1st Eval PR	Pilot M, 2nd Eval PR	Pilot W, 1st Eval PR	Pilot W, 2nd Eval PR	Pilot M, 1st Eval PIOR	Pilot M, 2nd Eval PIOR	Pilot W, 1st Eval PIOR	Pilot W, 2nd Eval PIOR
1	1a	5	2	6	4	5		2.5	1.5	2	
2	1b	3.25	1.25	3.5		3		1		1.5	
3	1c	4	2	5	3.5	4		2.5	2	1.5	
4	1d	4.25	2	5	4.5	3	4	2.5	2	1	2
5	1e	6	3.5	6				3.5			
6	1f	8	4	8		8		4		4	
7	1g	8.5	4.25	8.5		8.5		4.5		4	
8	2a	4.25	2	4.5		4		2		2	
9	2b	5.5	2.5	6	6	4	5	2.5	3	1.5	2.5
10	2c	3	1.5	3				1.5			
11	2d	2.5	1	3	2.5	2.5		2	1	1	
12	2e	4	1	4				1			
13	2f	3	1	3				1			
14	2g	7	3	7				3			
15	2h	5.5	2.5	5	6	5.5		2.5	2.5	2	
16	2i	8	4.25	8		8		4.5		4	
17	2j	6	2	6		6		2		2	
18	3a	4	1.5	5	4	4	4	3	1.5	1	1.5
19	3b	4.5	2	4.5				2			
20	3c	3.5	1.5	4		3		2		1	
21	3d	4	1.5	4		4		2		1	
22	3e	4	1.25	4		4		1.5		1	
23	4a	5.25	2.25	5.5		5		2.5		2	
24	4b	7	4			7				4	
25	4c	8.5	4	8.5				4			
26	4d	8.5	4.25	8	9			3.5	5		
27	4e	7.5	4	7.5				4			
28	5a	6	3	7		5	6	3		1.5	3
29	5b	7	4			7				4	
30	5c	8	4.5	9		7		5		4	
31	5d	9	4	8.5	9	9		4	5	4	
32	5e	8	4	8		8		4		4	
33	6a	5.5	2.5	5		6		2		3	
34	6b	2.5	1.5	2.5	1	4		1.5	1	1.5	
35	6c	4.5	2.25	4		5		2.5		2	
36	6d	5.5	2.5	5.5				2.5			
37	6e	7.75	4.5	8.5		7		5		4	
38	6f	8.5	4	8		8.5	10	4		4	5
39	7a	4	2	5	4	2		2	2	1	
40	7b	3	1.5	3				1.5			
41	7c	3	1.5	3	3	4	1.5	2	2	1	1

Table E-I
Neal-Smith Evaluation Data Summary (Cont.)

No.	Config-uration	Median PR	Median PIOR	Pilot M, 1st Eval PR	Pilot M, 2nd Eval PR	Pilot W, 1st Eval PR	Pilot W, 2nd Eval PR	Pilot M, 1st Eval PIOR	Pilot M, 2nd Eval PIOR	Pilot W, 1st Eval PIOR	Pilot W, 2nd Eval PIOR
42	7d	5.5	3	5.5				3			
43	7e	5.5	2.5	6		5		3		2	
44	7f	5.5	2.75	3	4	7	7	2	2	3.5	4
45	7g	5.5	2	5		6		2		2	
46	7h	5	2			5				2	
47	8a	4.5	1.75	5		4		2.5		1	
48	8b	3.5	1.5	3.5				1.5			
49	8c	3.25	1.5	3.5		3		2		1	
50	8d	3	1.5	2		4		1		2	
51	8e	3	1	2.5	3	5		1	1	2	

Notes:

1) Ratings taken from Table I of AFFDL-TR-70-74.

2) Configuration 7f was evaluated by each pilot three times. The 2nd and 3rd evaluation ratings are given for Pilot W rather than the 1st and 2nd. The 3rd evaluation by Pilot M was a PR of 4 and PIOR of 2; the 1st Eval by Pilot W was a PR of 7 with no PIOR given.

3) Additional position command system configurations not used in analysis because of sparse rating data.

4) Ratings which were identified as anomalous by the authors were not used in the summary.

Table E-II
LAHOS Evaluation Data Summary

No.	Configuration	Median PR	Median PIOR	Pilot A, 1st Eval PR	Pilot A, 2nd Eval PR	Pilot B, 1st Eval PR	Pilot B, 2nd Eval PR	Pilot A, 1st Eval PIOR	Pilot A, 2nd Eval PIOR	Pilot B, 1st Eval PIOR	Pilot B, 2nd Eval PIOR
1	1-a	6	1	6				1			
2	1-b	5	2	5				2			
3	1-c	4	1	4		4		1		1	
4	1-1	4	1.5	4		4		2		1	
5	1-2	5	2	5				2			
6	1-3	9.5	4	9		10		4		4	
7	1-4	10	4	10				4			
8	1-6	5	2	5				2			
9	1-8	8	3			8				3	
10	1-11	9	3.5	9				3.5			
11	2-a	5	2.25	4		6		2		2.5	
12	2-c	2.25	1	4	1.5	1.5	3	2	1	1	1
13	2-1	2	1	2		2		1		1	
14	2-2	4.25	1.5	4.5		4		1		2	
15	2-3	6	3	6				3			
16	2-4	9	3	9				3			
17	2-6	5	2.5	5				2.5			
18	2-7	6.5	3	7		6		3		3	
19	2-9	10	3			10				3	
20	2-10	10	4	10				4			
21	2-11	8	3			8				3	
22	3-c	3.5	1.25	2		5		1		1.5	
23	3-0	4.5	1.5	4	5			1	2		
24	3-1	5	2	4	5	7		2	2	3	
25	3-2	7	3	7				3			
26	3-3	10	4	10				4			
27	3-6	6.5	3	7		6		3		3	
28	3-7	8	4	8				4			
29	4-c	3	1.75	3		3		1.5		2	
30	4-1	2	1	2				1			
31	4-3	7	3	5	7	8		2	3	3	
32	4-4	6.5	3	7		6		3		3	
33	4-6	4	2	4				2			
34	4-7	3	1	3				1			
35	4-10	9	4	9				4			
36	4-11	8	4	8				4			
37	5-1	6	3	7		5		3		3	
38	5-3	6	3	8	4.5	6		3	2.5	3	
39	5-4	6	2.5	6				2.5			
40	5-5	7	3	7				3			
41	5-6	6	3			6				3	

Table E-II
LAHOS Evaluation Data Summary (Cont.)

No.	Config-uration	Median PR	Median PIOR	Pilot A, 1st Eval PR	Pilot A, 2nd Eval PR	Pilot B, 1st Eval PR	Pilot B, 2nd Eval PR	Pilot A, 1st Eval PIOR	Pilot A, 2nd Eval PIOR	Pilot B, 1st Eval PIOR	Pilot B, 2nd Eval PIOR
42	5-7	6	3	6				3			
43	5-11	7	3.5	7				3.5			
44	6-1	10	4	10				4			
45	6-2	2	1	2				1			

Notes:

1) Overall ratings used exclusively; no approach only or touchdown only ratings used.
2) For configuration 2-c, all ratings are for Pilot A; Pilot B did not evaluate this configuration.
3) Configuration 4-0 was not used; this configuration was only evaluated once and the rating data appears to be anomalous.
4) Configuration series 7 data was not used.

Table E-III
TIFS Pitch Rate Program Evaluation Data Summary

No.	Config	Median PR	Median PIOR	Pilot A, 1st Eval PR	Pilot A, 2nd Eval PR	Pilot B, 1st Eval PR	Pilot B, 2nd Eval PR	Pilot A, 1st Eval PIOR	Pilot A, 2nd Eval PIOR	Pilot B, 1st Eval PIOR	Pilot B, 2nd Eval PIOR
1	1-1-1	6	2.5	5		7		2		3	
2	1-2-2	7	4	8	7	5.5		4	2	4	
3	1-3-7	4	1	3	4	7		1	1	4	
4	2-1-1	7	3	6	7	7		4	3	3	
5	2-2-2	3.75	2	4.5		3		2		2	
6	3-1-3	5.75	3	5.5		6		3		3	
7	3-2-4	3.75	1	2.5		5		1		1	
8	4-1-1	3.75	1	2.5		5		1		1	
9	4-2-2	2.5	1	2		3		1		1	
10	4-3-7	7	1			7				1	
11	4-3-7-1	4	1	4				1			
12	5-1-1	4.5	2.5	4.5		4.5		2		3	
13	5-2-2	2.5	1	2		3		1		1	
14	6-1-1	5.5	2.5	3	5	6	6	1	2	3	4
15	6-1-1-1	4	1			4				1	
16	6-2-1	4	1	5	4	2		1	1	1	
17	6-2-1-1	3	1			3				1	
18	7-1-4	2.75	1	3		2.5		1		1	
19	8-1-5	5.5	1	4	5.5	6		1	2	1	
20	8-1-5-1	2	1	2				1			
21	8-2-5	7.5	4	8	8	7		4	4	4	
22	8-2-5-1	7	4	7				4			
23	8-3-5	7	3	5	8	7	7	3	4	3	3
24	8-3-5-1	3	1.25	2.5	3			1	1.5		
25	8-4-6	1	1	1				1			
26	8-5-5	6	3.5	5	7			3	4		
27	8-5-5-1	4	2	4				2			

Notes:

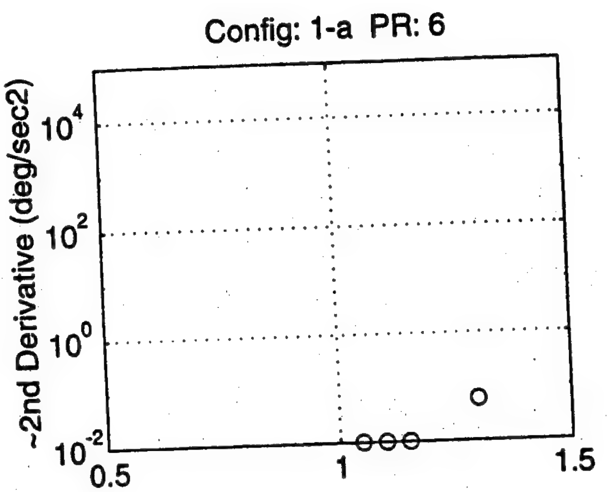
1) Overall ratings used from pilot comment summaries.

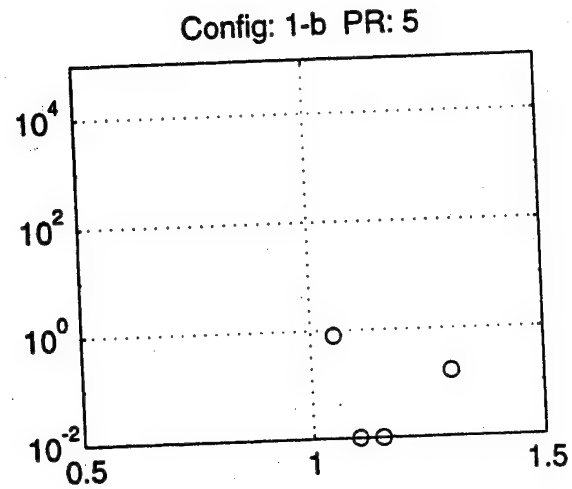
2) For configuration 8-3-5, the ratings for Pilot B, second evaluation, are actually the third evaluation ratings data for Pilot A.

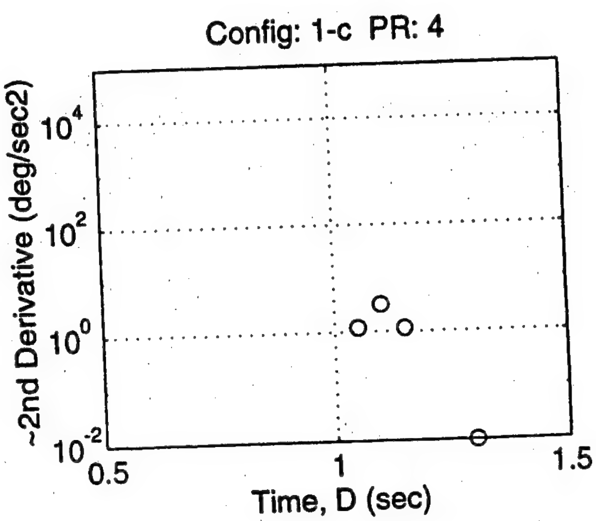
3) Configurations which were considered to be anomalous and discarded by the authors were not used. However, ratings for configurations 4-3-7 and 8-2-5-1 are included because they were included in the report analysis even though the authors considered the evaluation to be suspect.

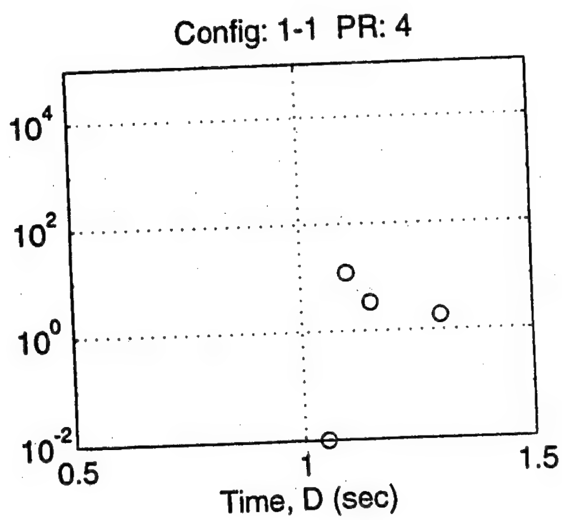
4) No pilot comments were available for configuations 1-2-2 (Pilot B), 2-1-1 (Pilot B), 5-1-1 (Pilot B), and 8-1-5 (Pilot A)

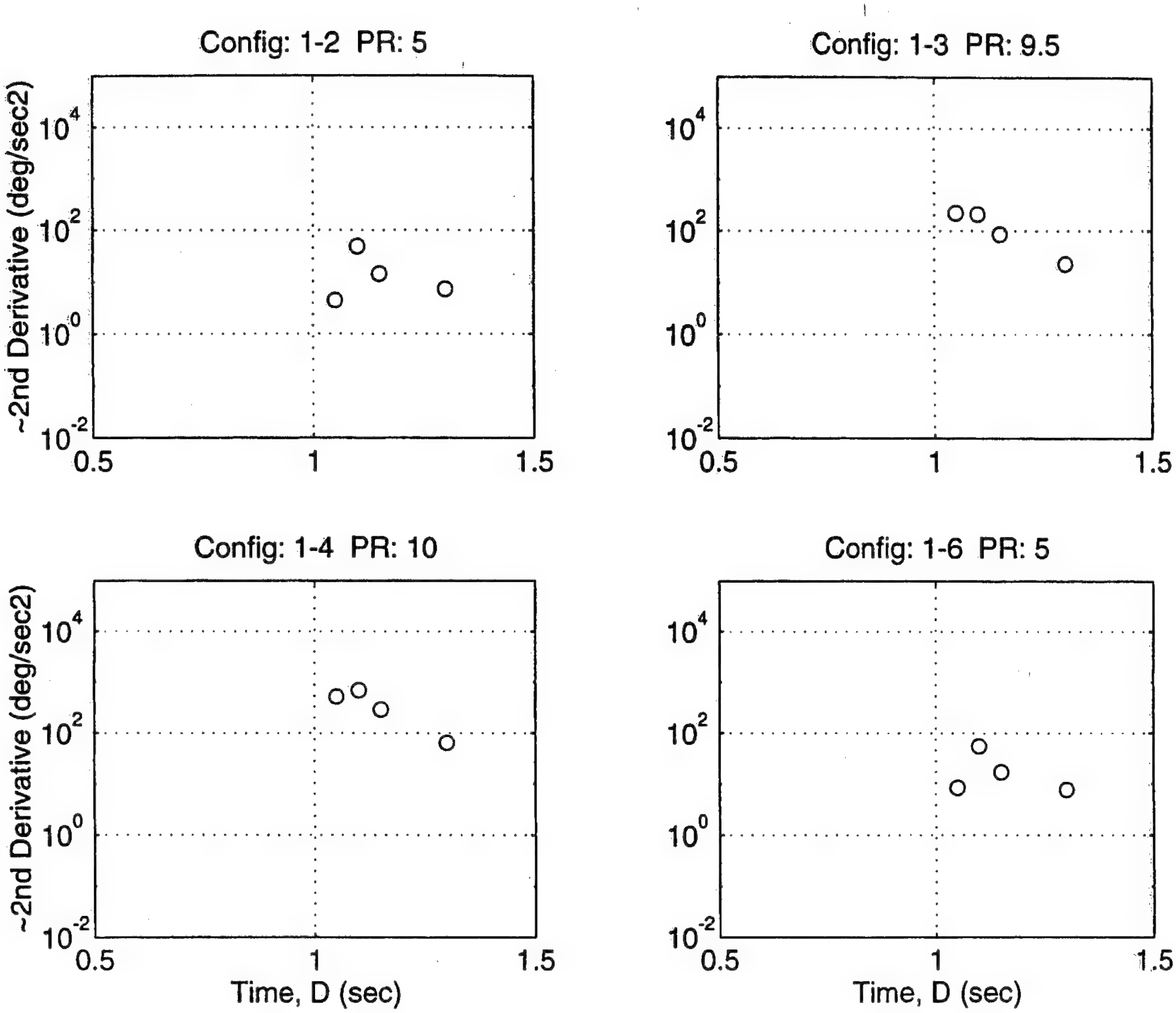
Appendix F
PIO Mappings

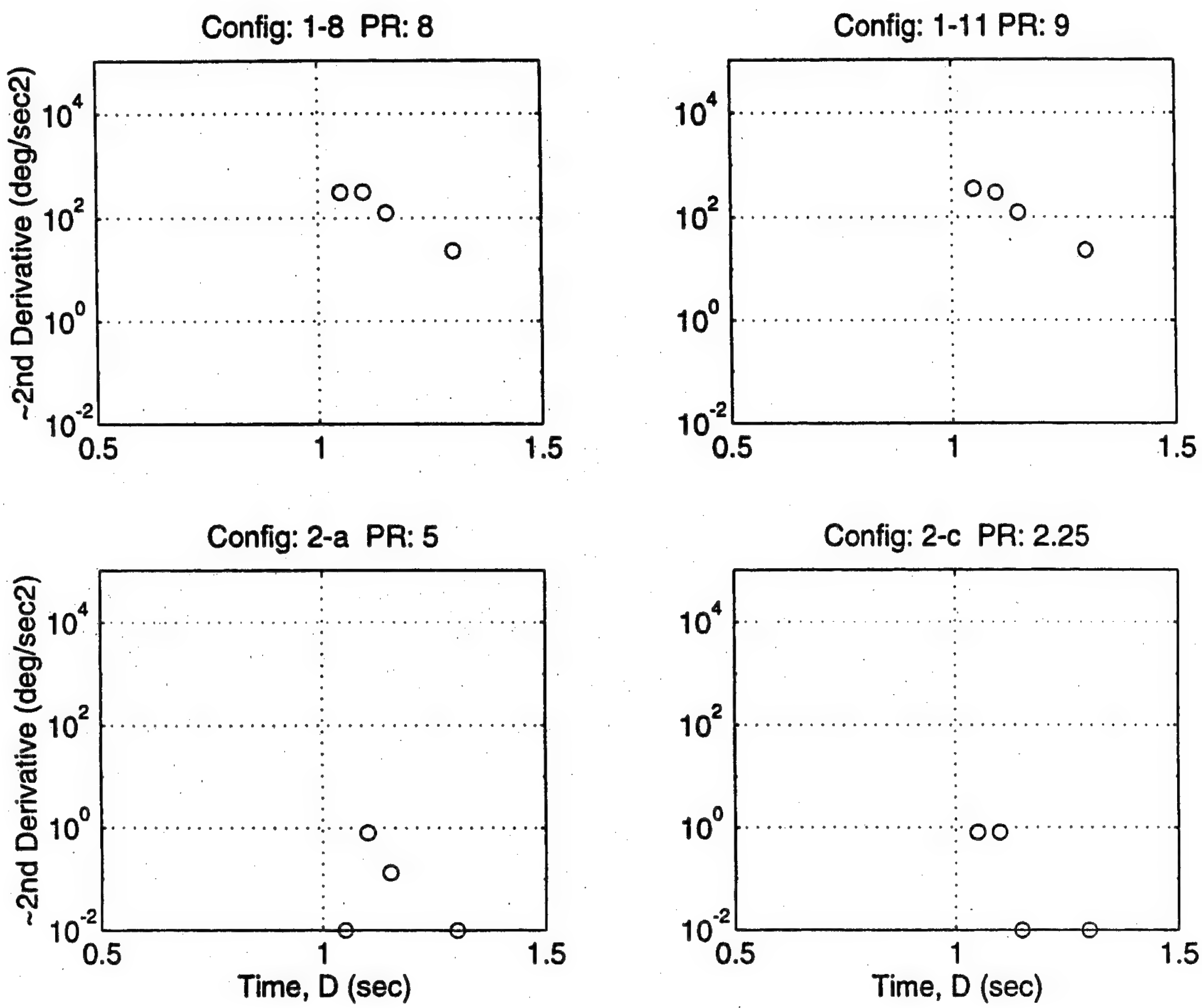


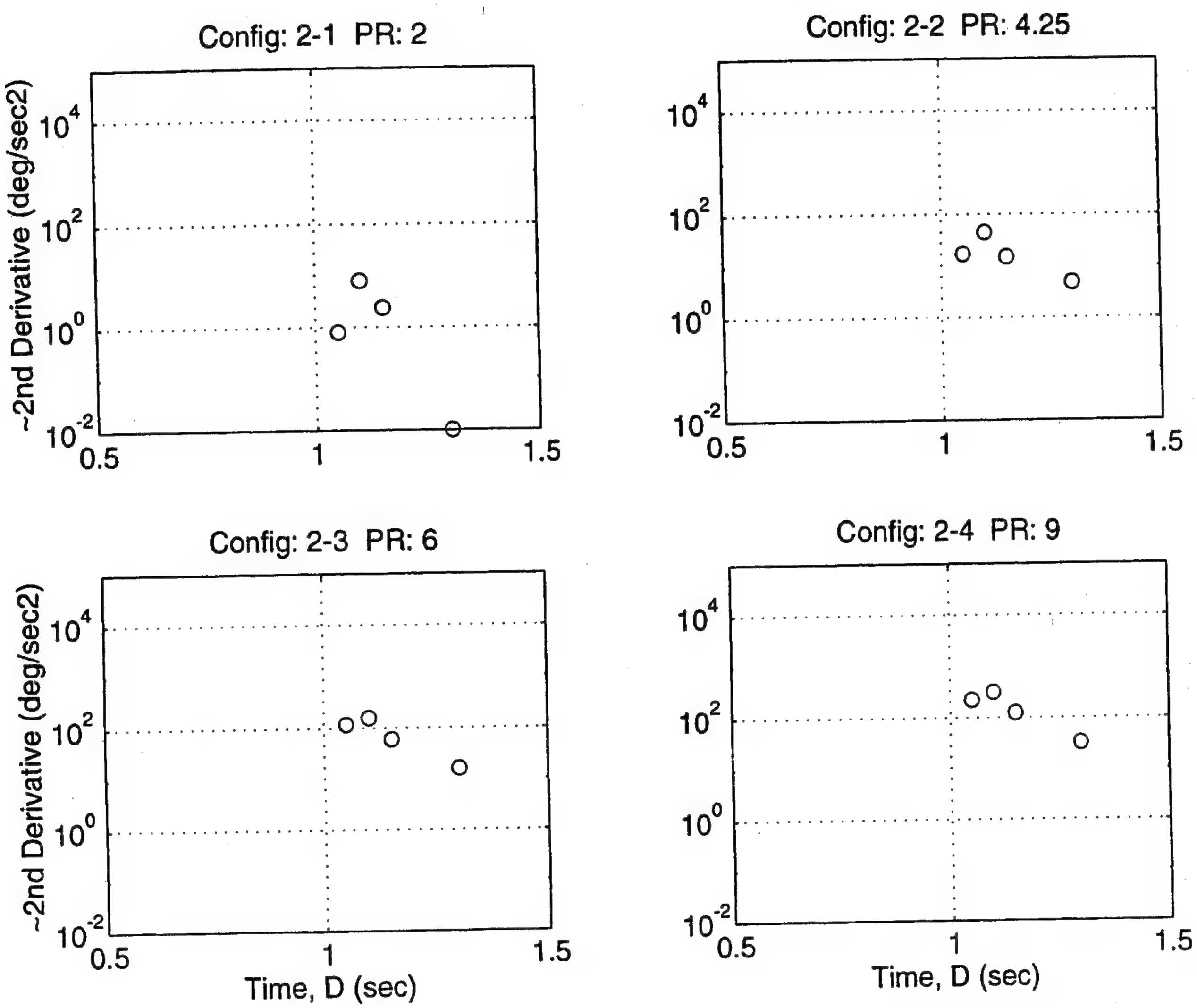




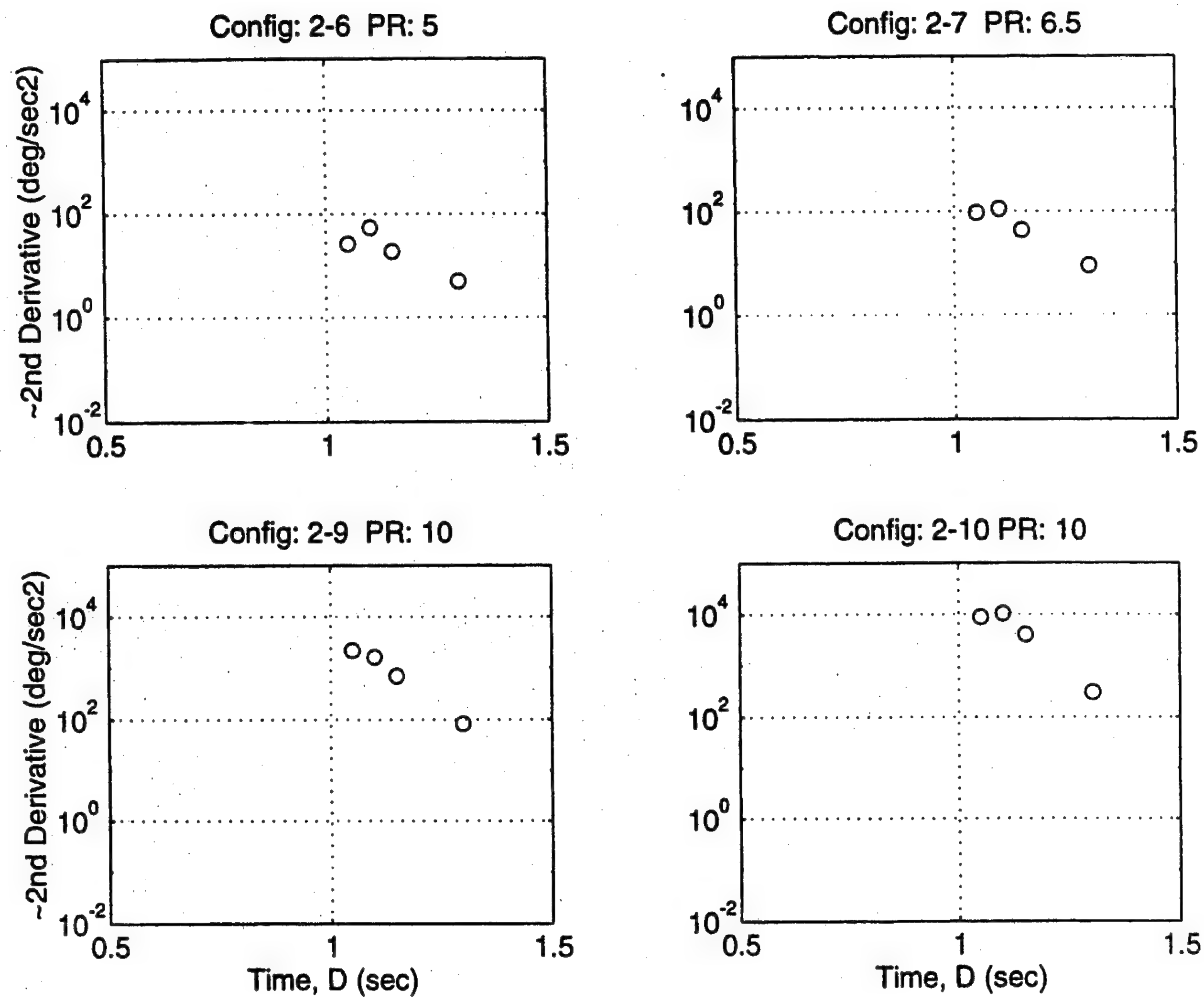


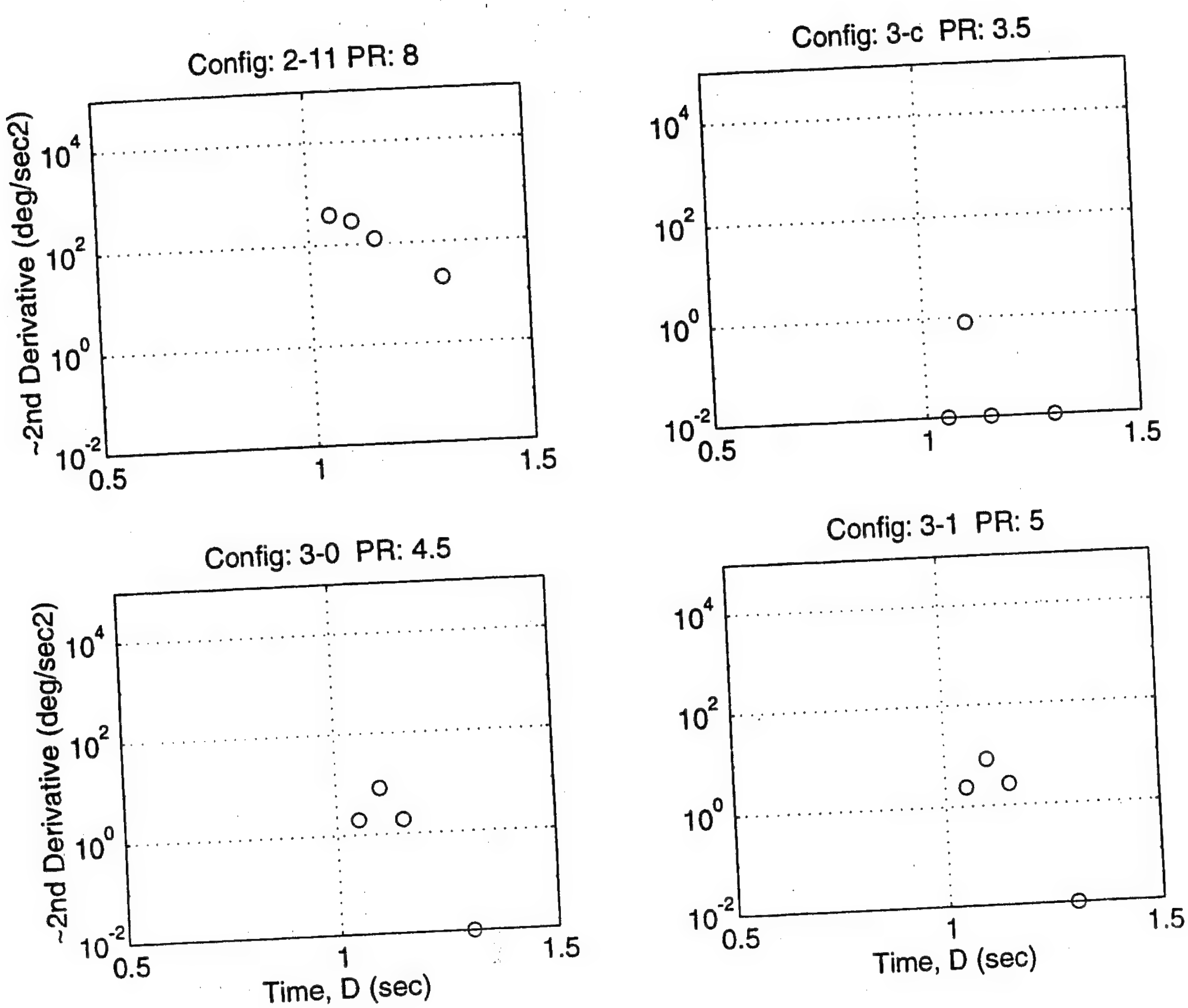

Config: 1-2 PR: 5
Config: 1-3 PR: 9.5
Config: 1-4 PR: 10
Config: 1-6 PR: 5
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5
Time, D (sec)


Config: 1-8 PR: 8
Config: 1-11 PR: 9
Config: 2-a PR: 5
Config: 2-c PR: 2.25
~2nd Derivative (deg/sec2)
10^{4}
10^{2}
10^{0}
10^{-2}
0.5
1
1.5
Time, D (sec)

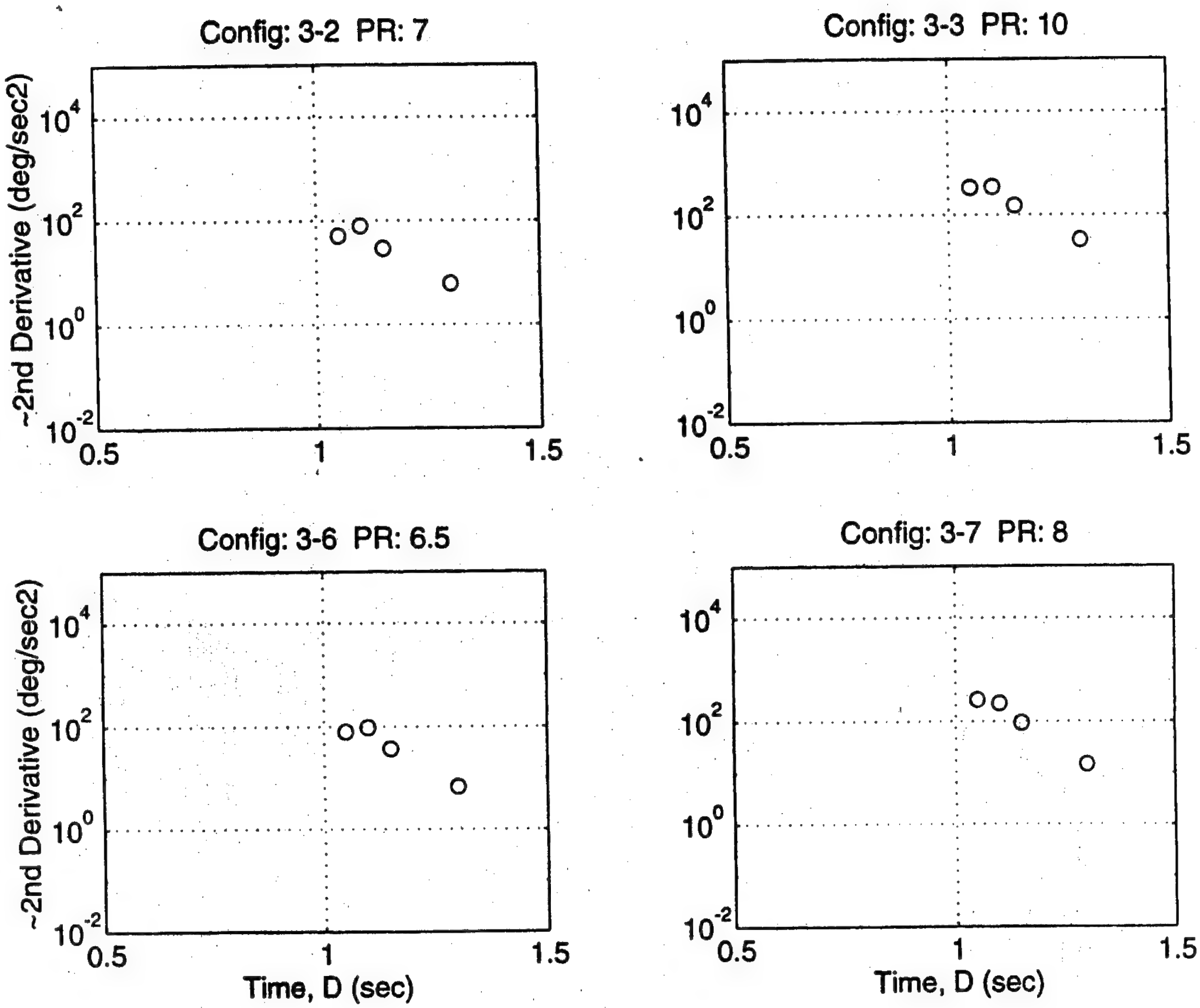


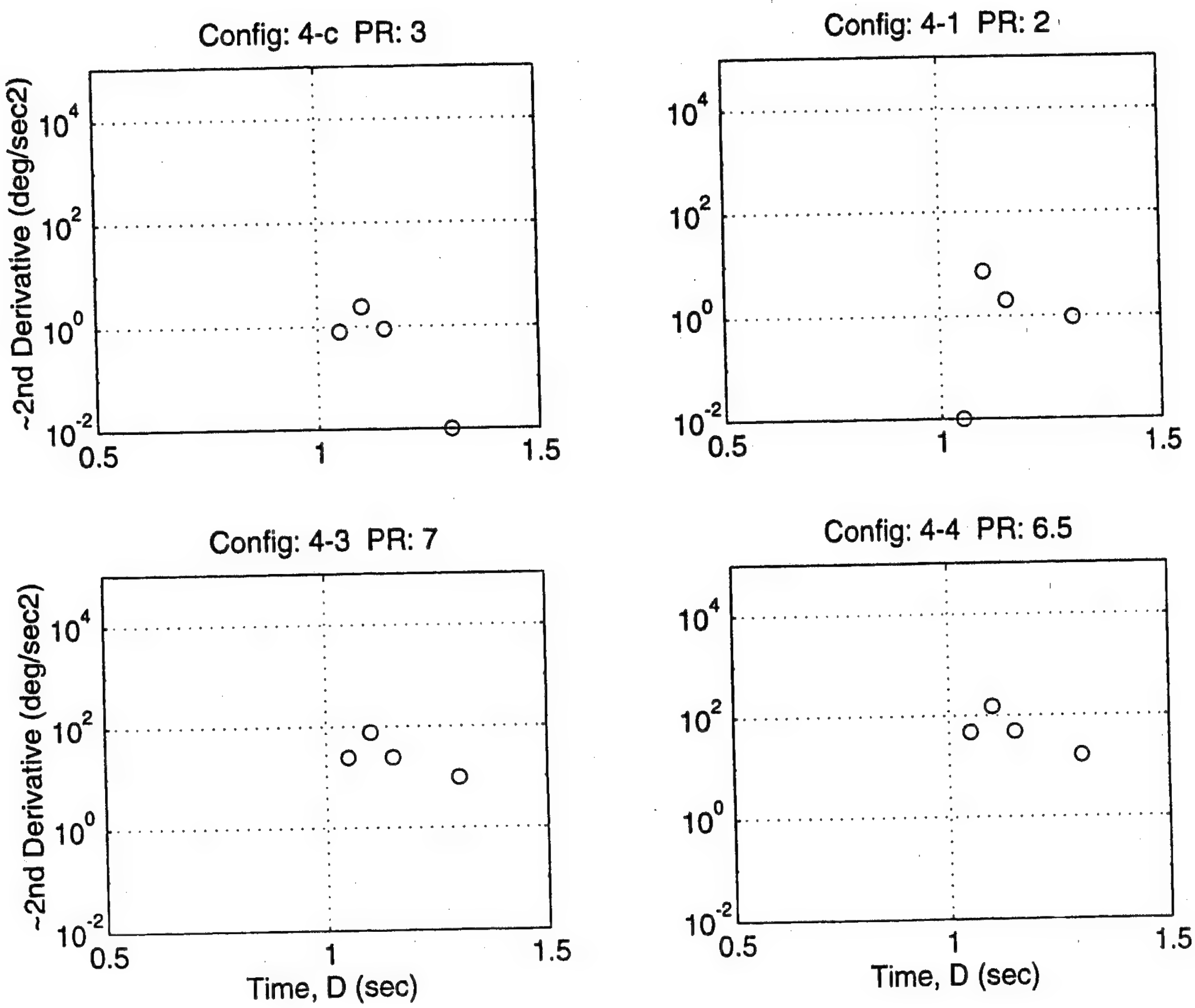
Config: 2-1 PR: 2
Config: 2-2 PR: 4.25
Config: 2-3 PR: 6
Config: 2-4 PR: 9
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5
Time, D (sec)


Config: 2-6 PR: 5
Config: 2-7 PR: 6.5
Config: 2-9 PR: 10
Config: 2-10 PR: 10
~2nd Derivative (deg/sec2)
Time, D (sec)

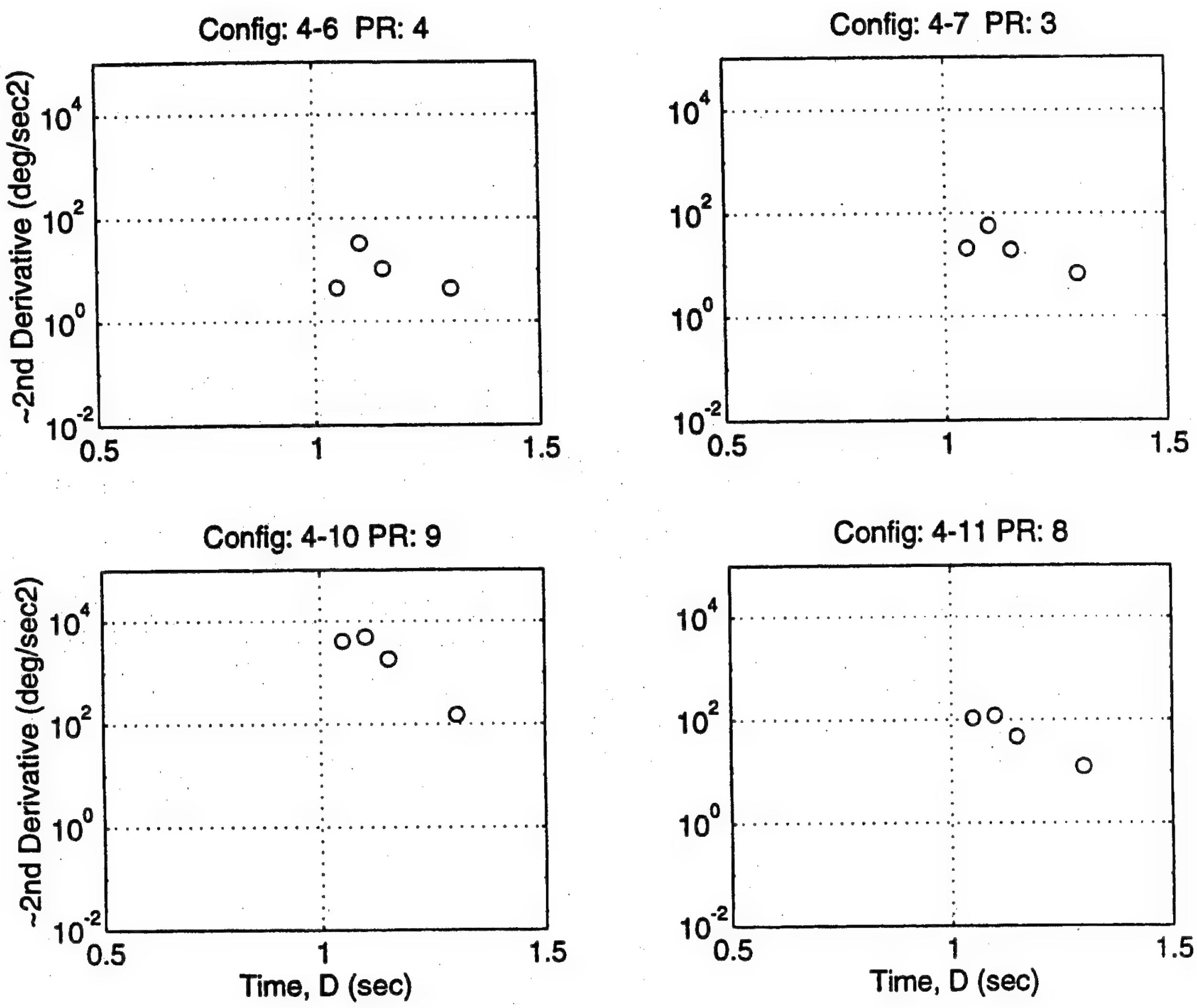


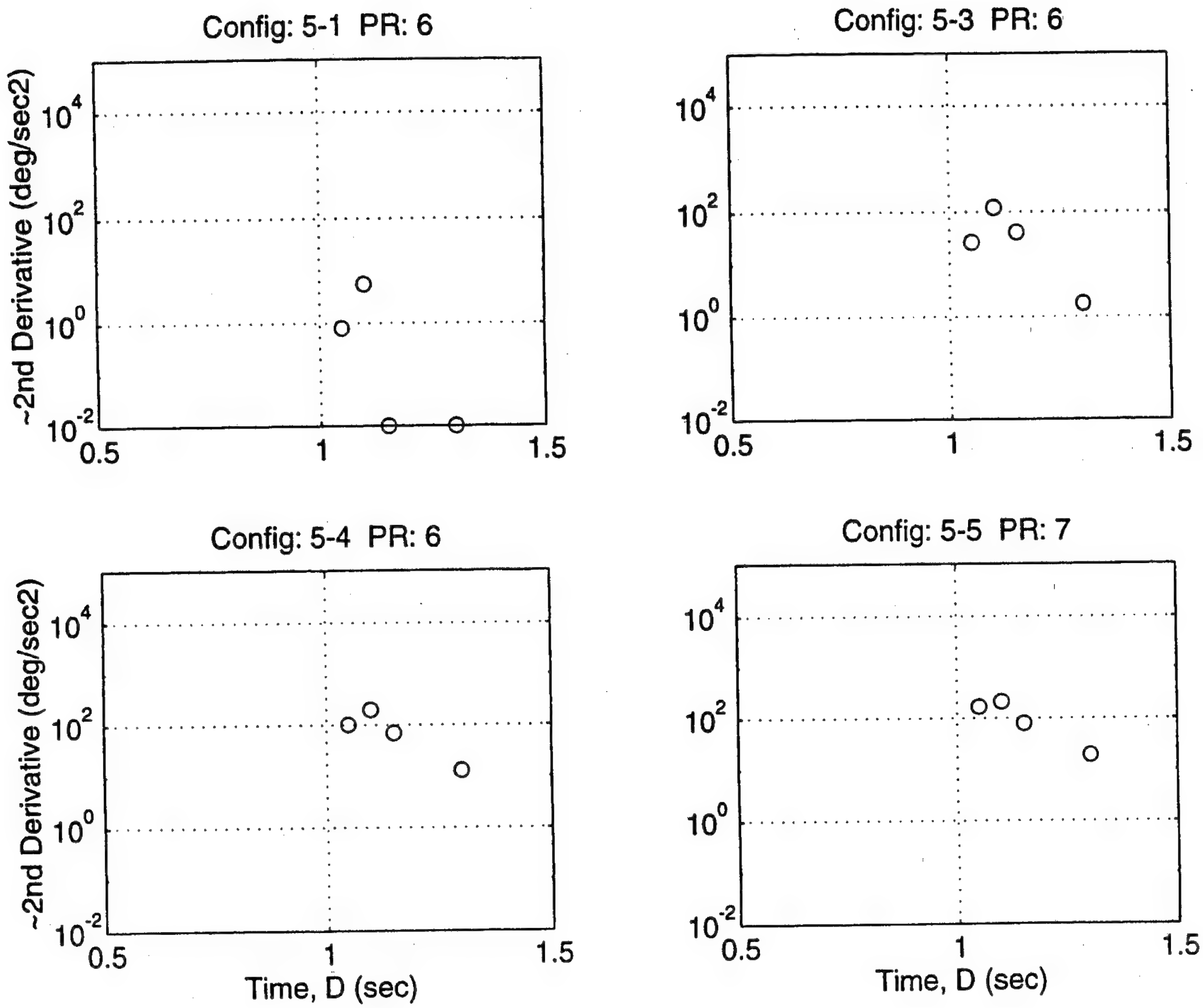
Config: 2-11 PR: 8
Config: 3-c PR: 3.5
Config: 3-0 PR: 4.5
Config: 3-1 PR: 5
~2nd Derivative (deg/sec2)
Time, D (sec)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5

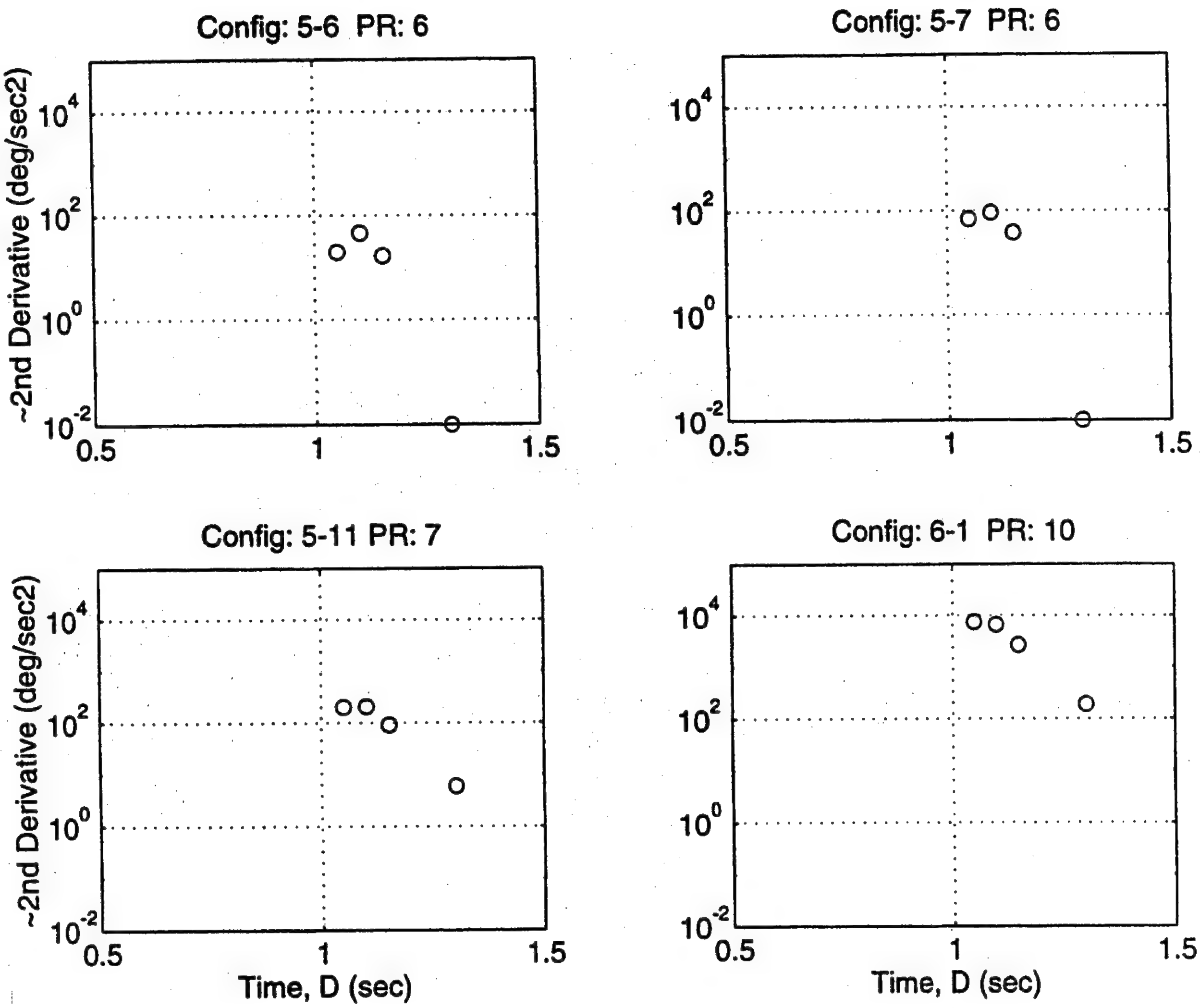

Config: 3-2 PR: 7
Config: 3-3 PR: 10
Config: 3-6 PR: 6.5
Config: 3-7 PR: 8
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)

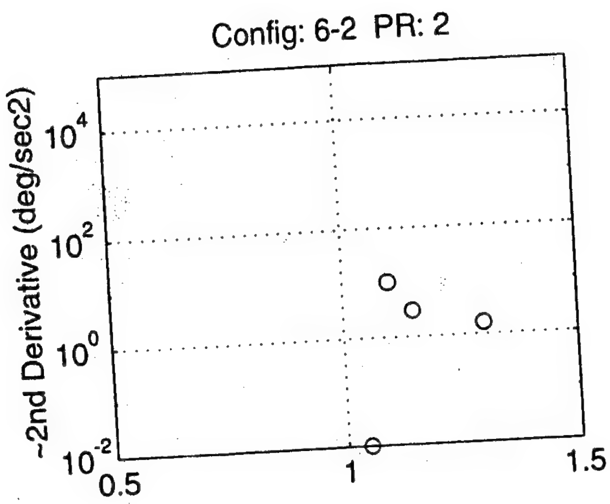


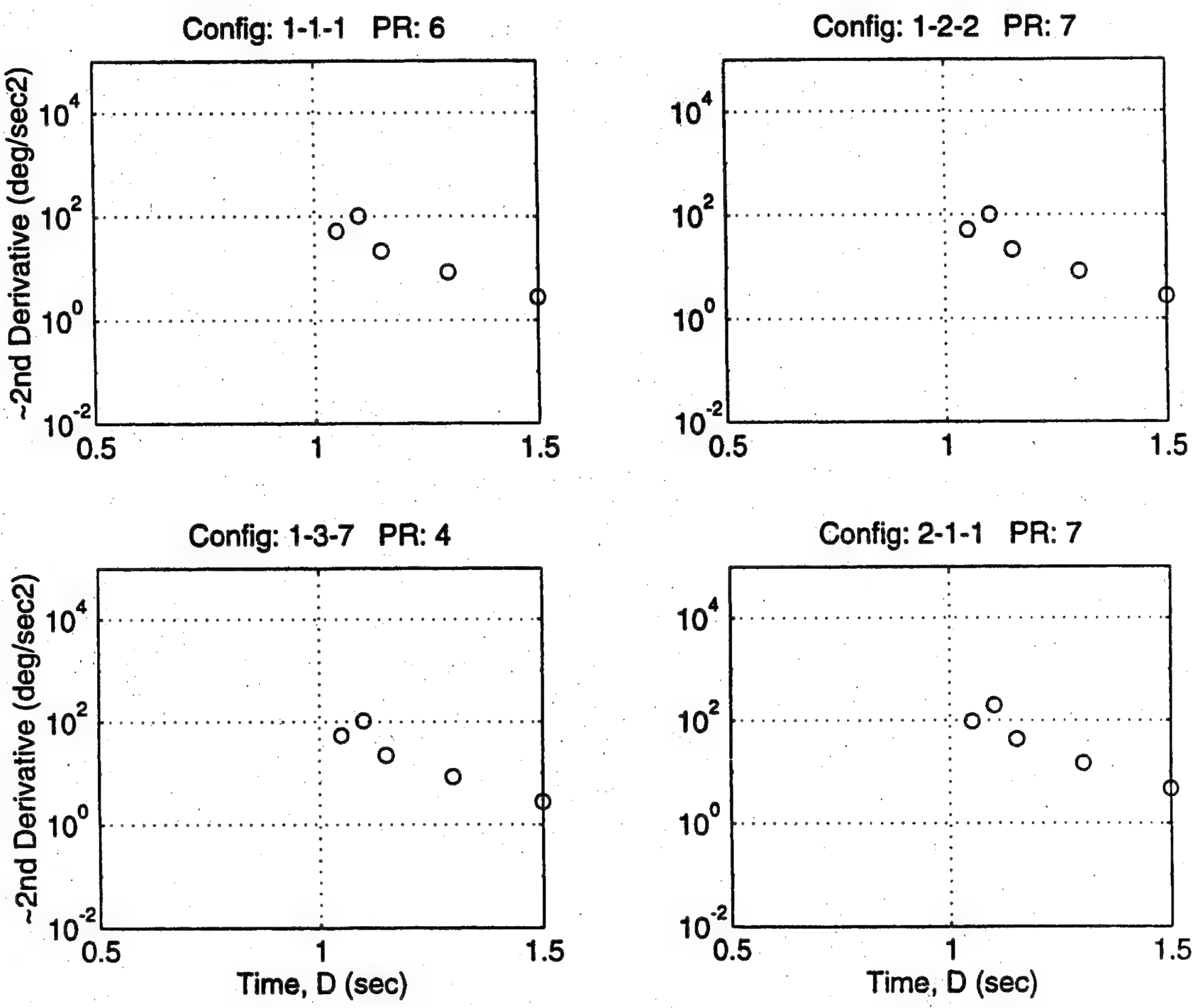
Config: 4-c PR: 3
Config: 4-1 PR: 2
Config: 4-3 PR: 7
Config: 4-4 PR: 6.5
~2nd Derivative (deg/sec2)
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5
Time, D (sec)
Time, D (sec)


Config: 4-6 PR: 4
Config: 4-7 PR: 3
Config: 4-10 PR: 9
Config: 4-11 PR: 8
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)

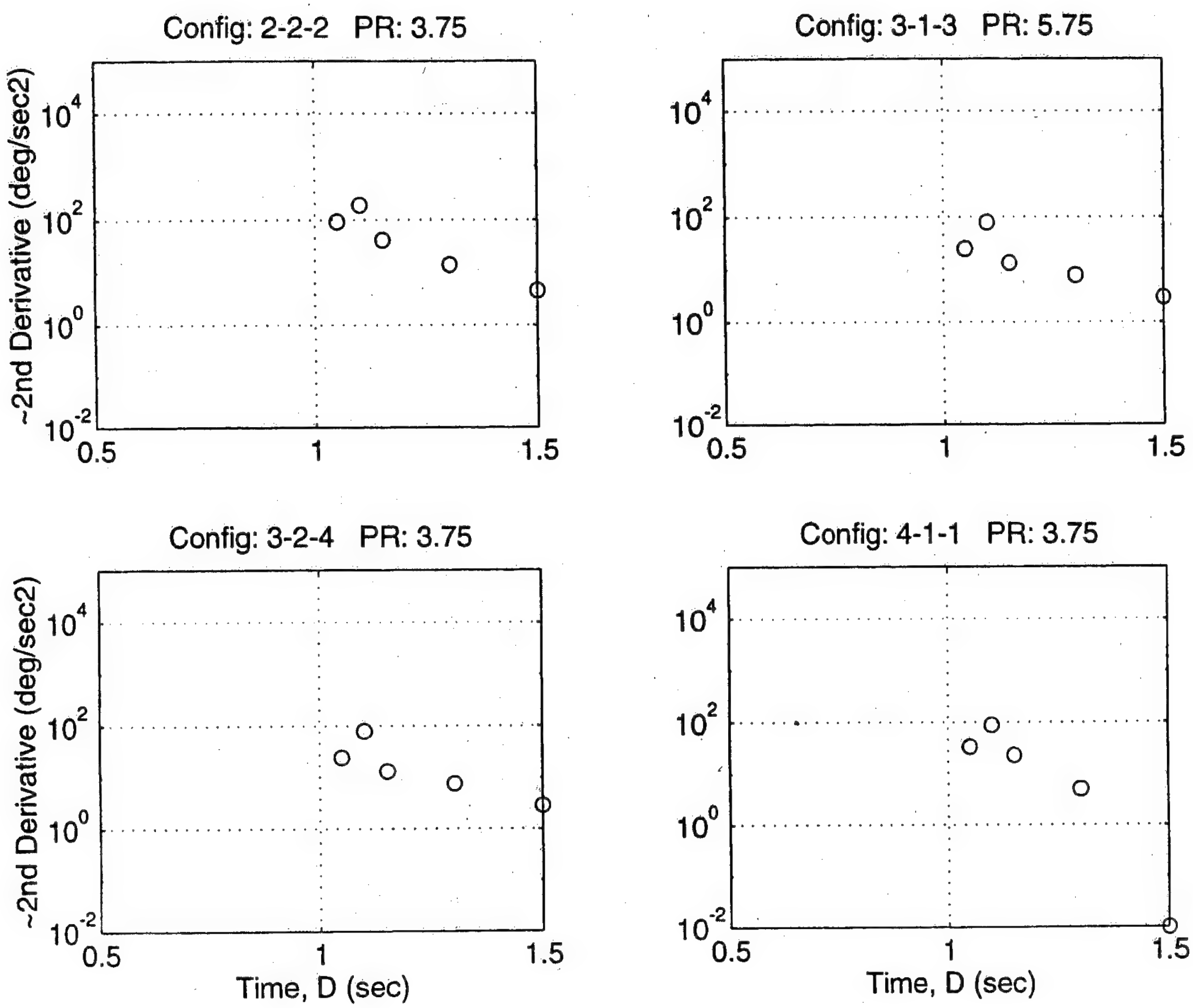

Config: 5-1 PR: 6
Config: 5-3 PR: 6
Config: 5-4 PR: 6
Config: 5-5 PR: 7
~2nd Derivative (deg/sec2)
Time, D (sec)
10^4
10^2
10^0
10^-2
0.5
1
1.5


Config: 5-6 PR: 6
Config: 5-7 PR: 6
Config: 5-11 PR: 7
Config: 6-1 PR: 10
~2nd Derivative (deg/sec2)
~2nd Derivative (deg/sec2)
Time, D (sec)
Time, D (sec)

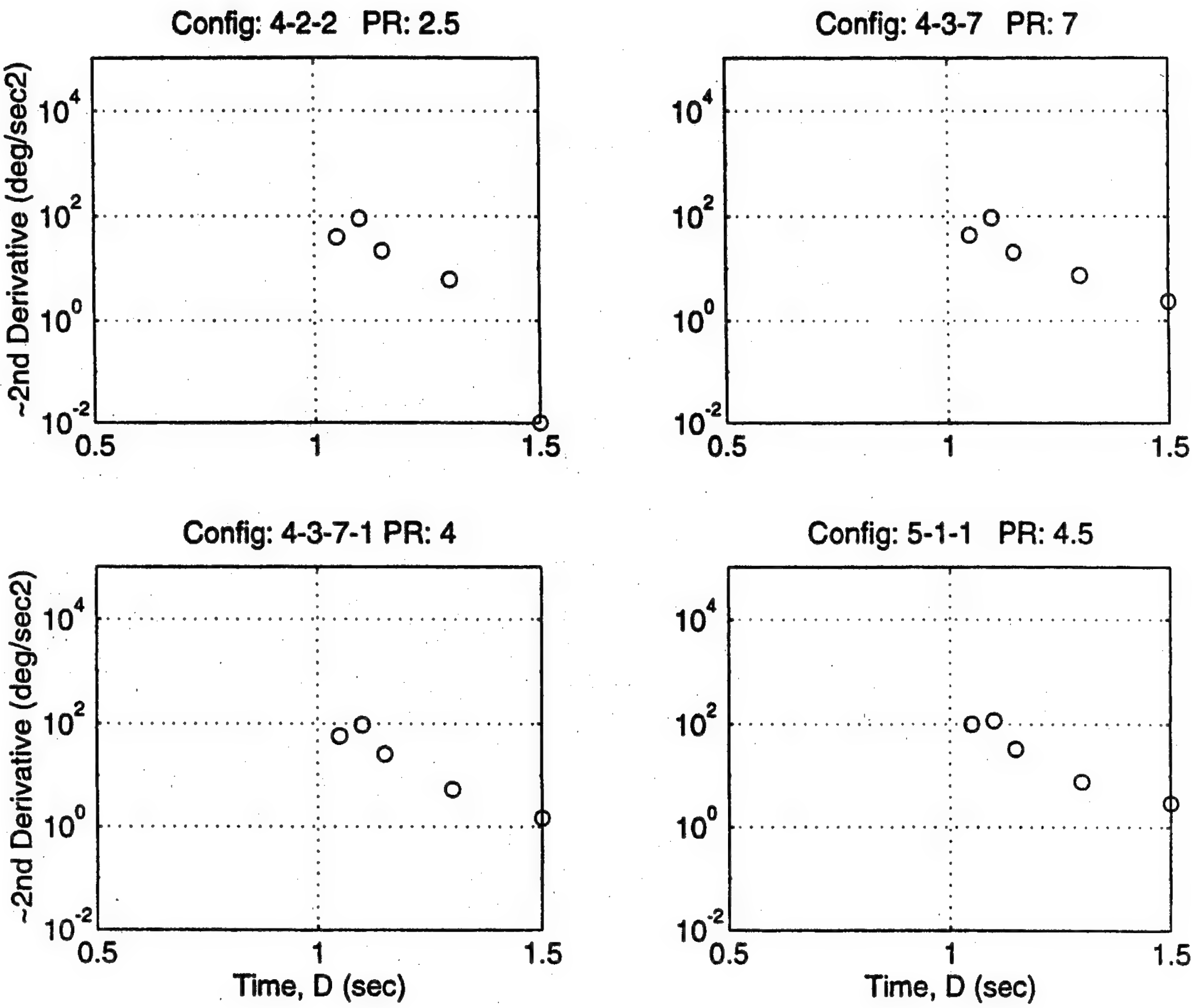

Config: 6-2 PR: 2
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5



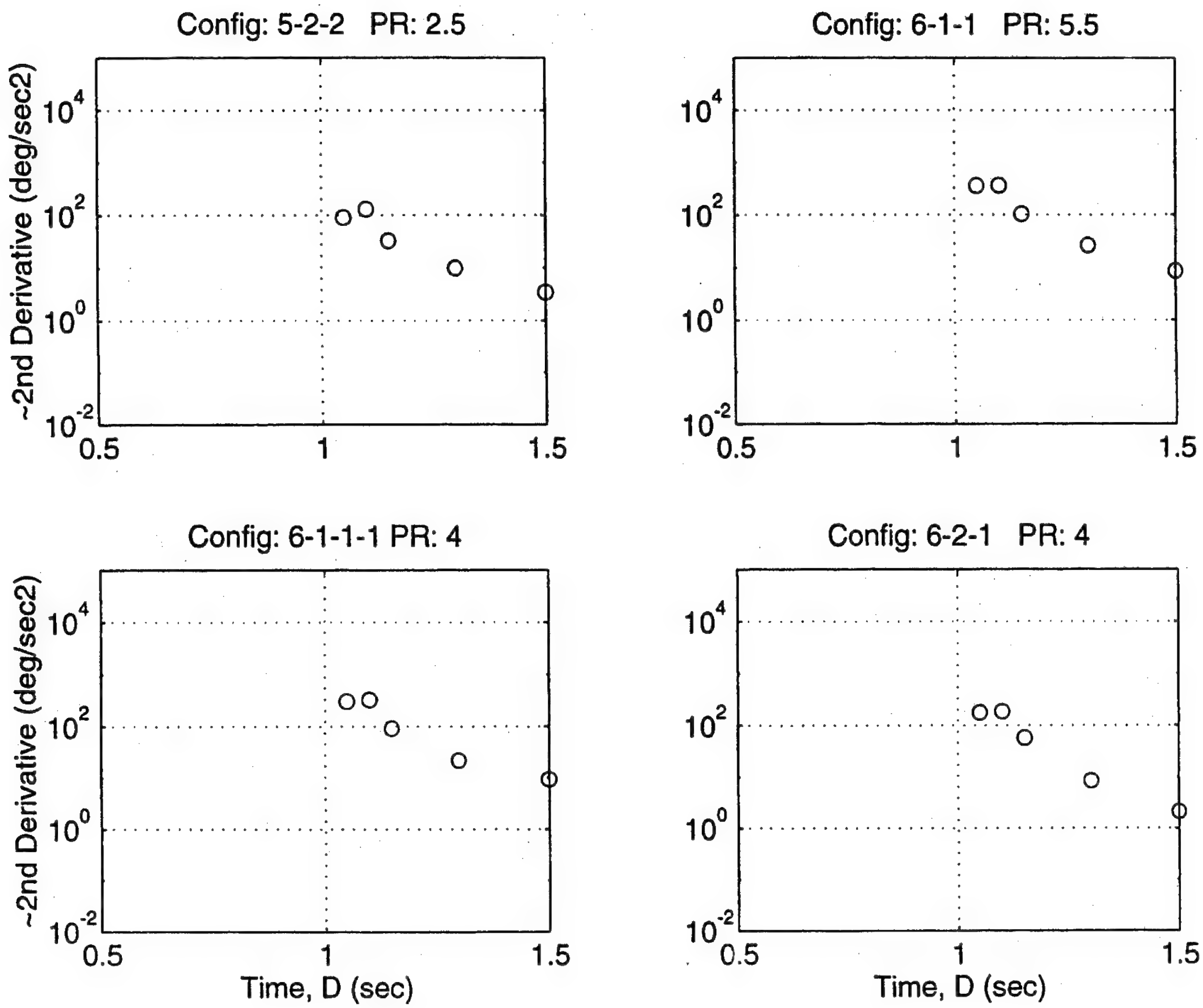
Config: 1-1-1 PR: 6
Config: 1-2-2 PR: 7
Config: 1-3-7 PR: 4
Config: 2-1-1 PR: 7
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)



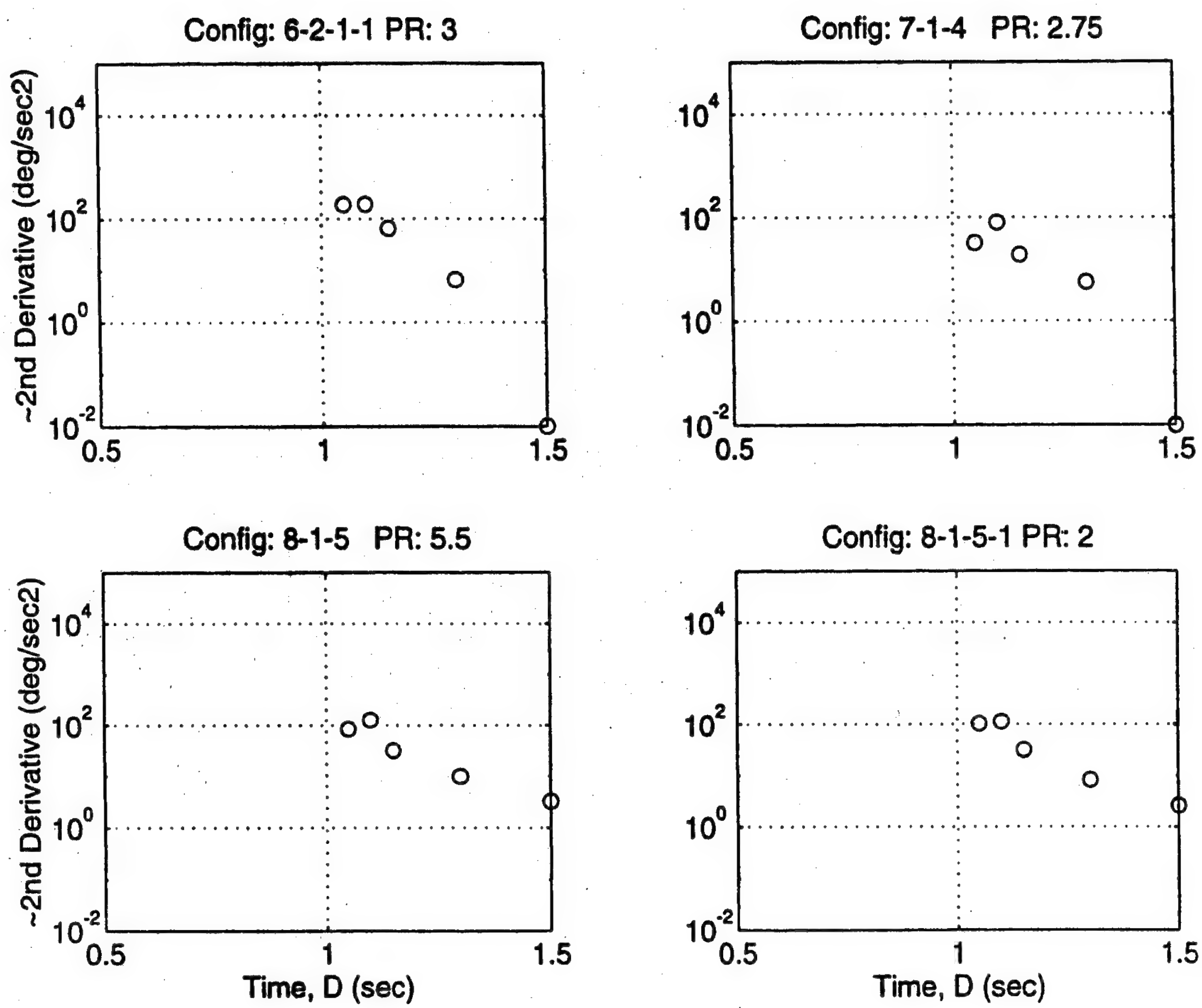
Config: 2-2-2 PR: 3.75
Config: 3-1-3 PR: 5.75
Config: 3-2-4 PR: 3.75
Config: 4-1-1 PR: 3.75
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)

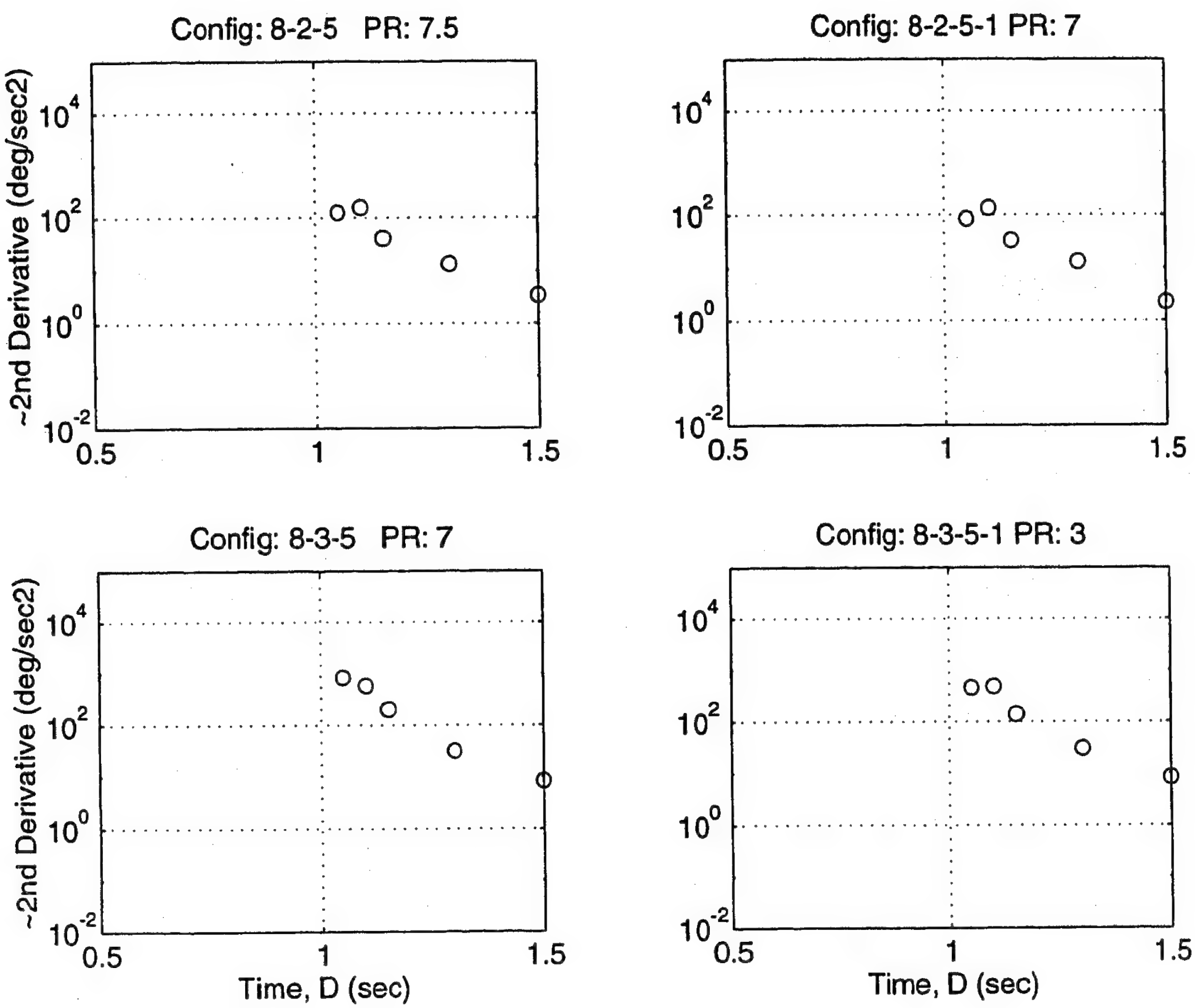


Config: 4-2-2 PR: 2.5
Config: 4-3-7 PR: 7
Config: 4-3-7-1 PR: 4
Config: 5-1-1 PR: 4.5
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)

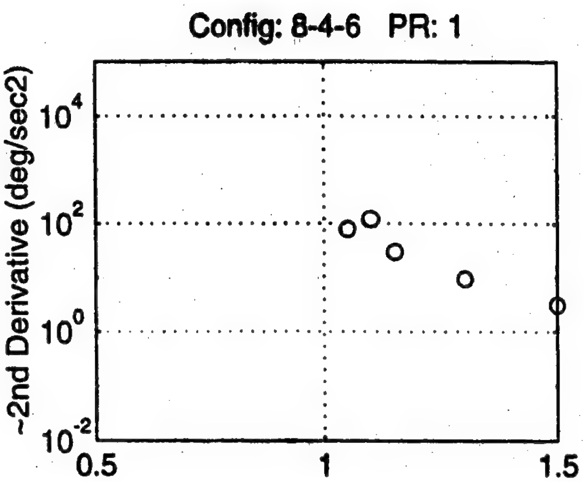


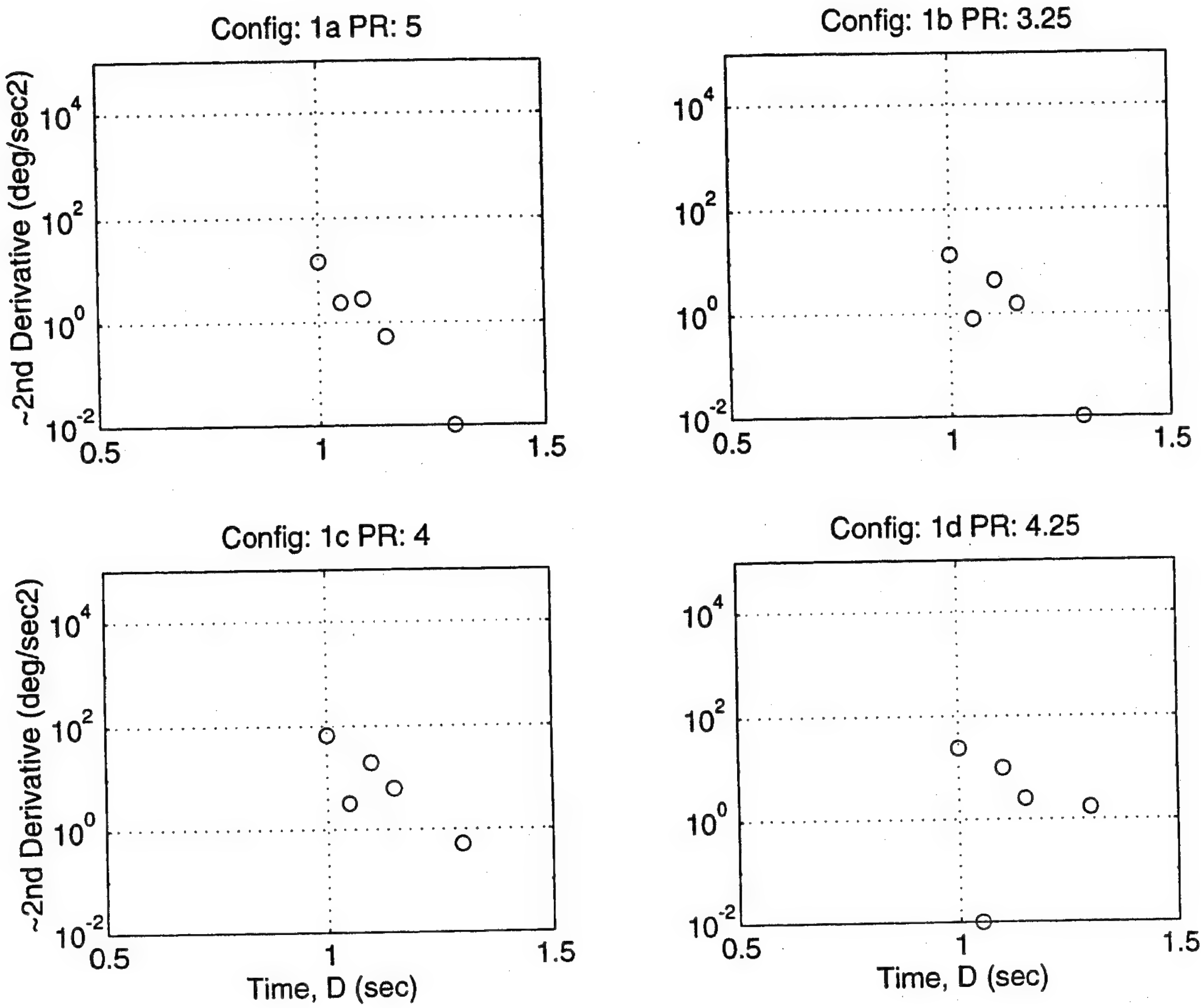
Config: 5-2-2 PR: 2.5
Config: 6-1-1 PR: 5.5
Config: 6-1-1-1 PR: 4
Config: 6-2-1 PR: 4
~2nd Derivative (deg/sec2)
Time, D (sec)

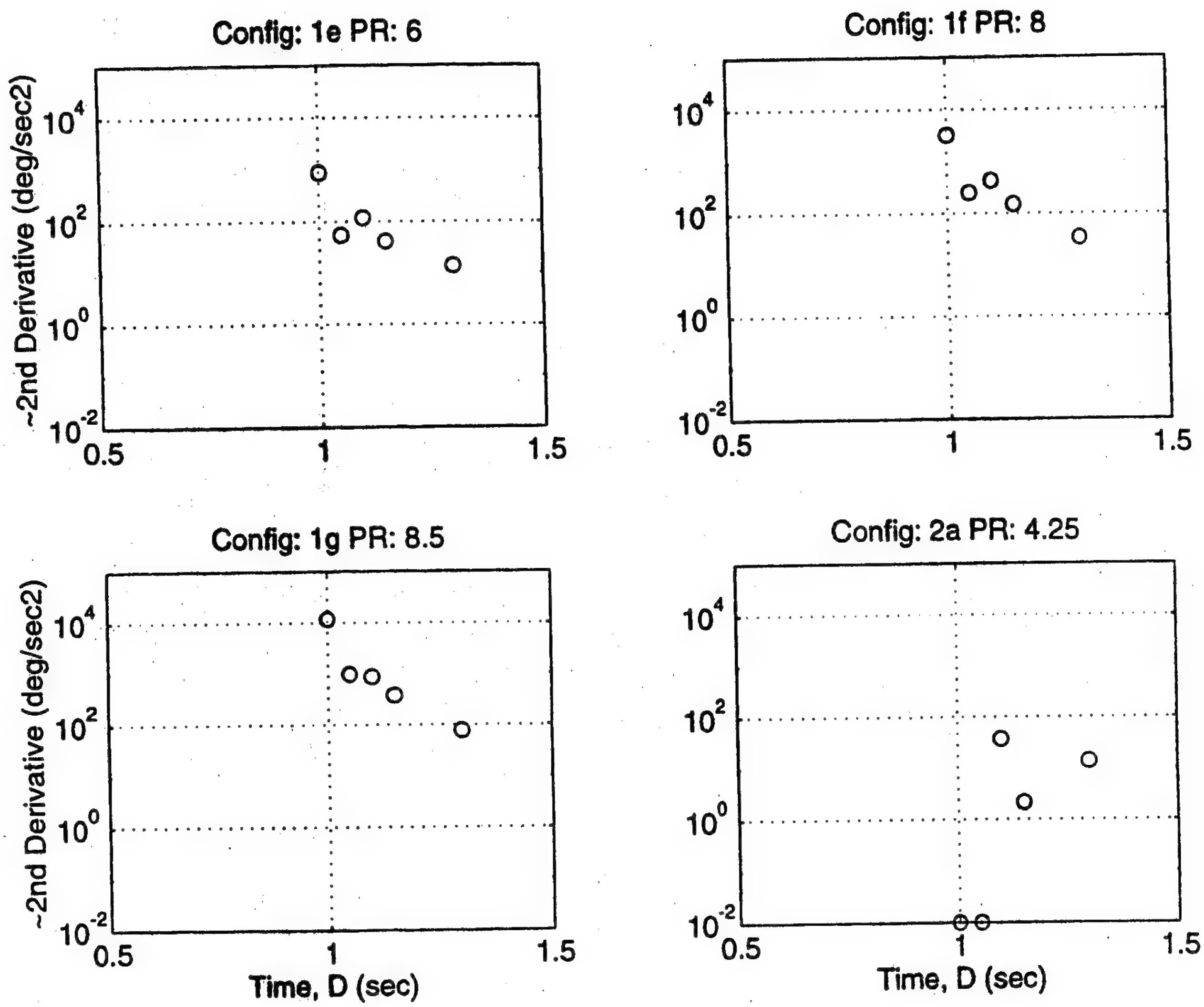

Config: 6-2-1-1 PR: 3
Config: 7-1-4 PR: 2.75
Config: 8-1-5 PR: 5.5
Config: 8-1-5-1 PR: 2
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)



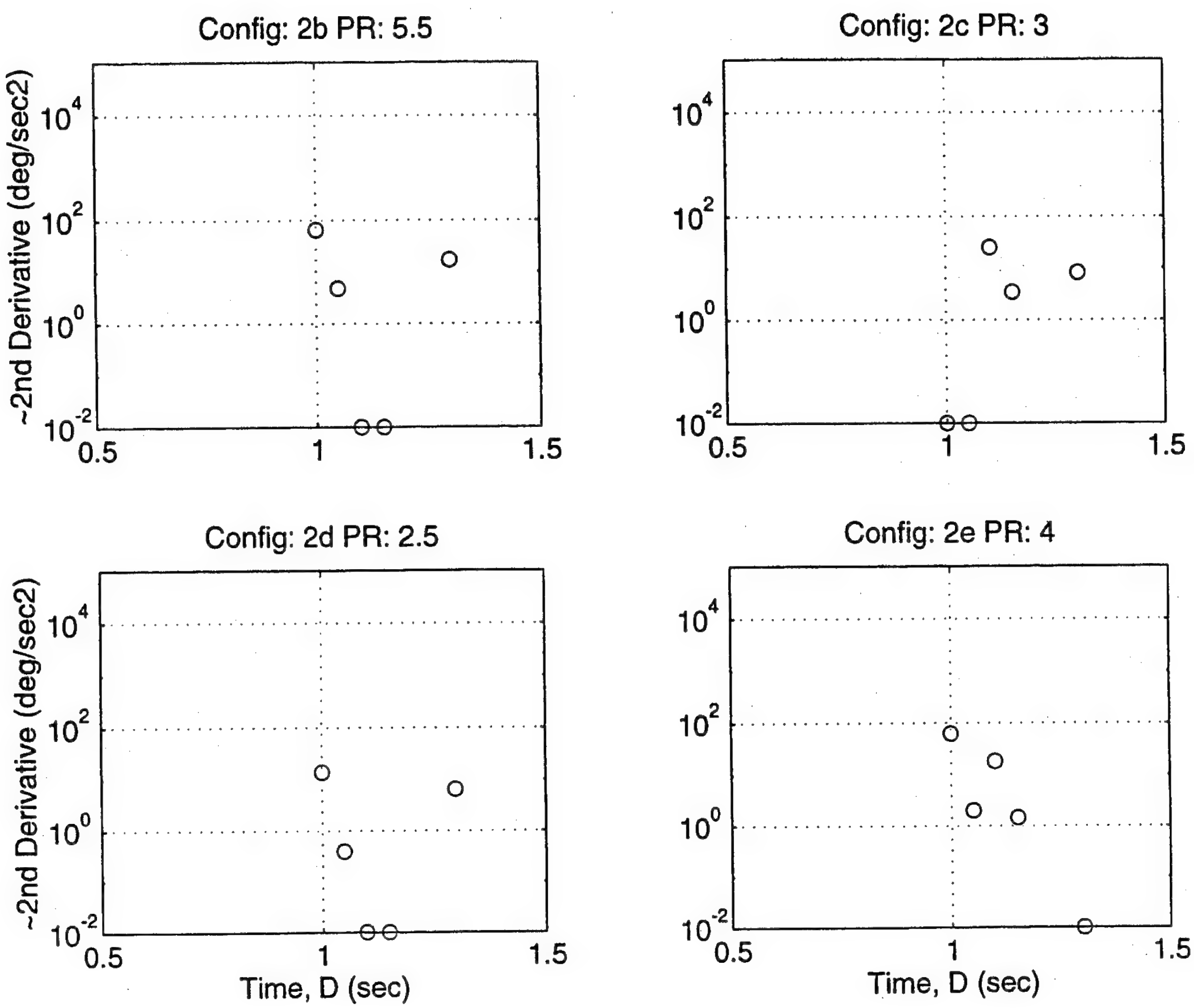
Config: 8-2-5 PR: 7.5
Config: 8-2-5-1 PR: 7
Config: 8-3-5 PR: 7
Config: 8-3-5-1 PR: 3
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)

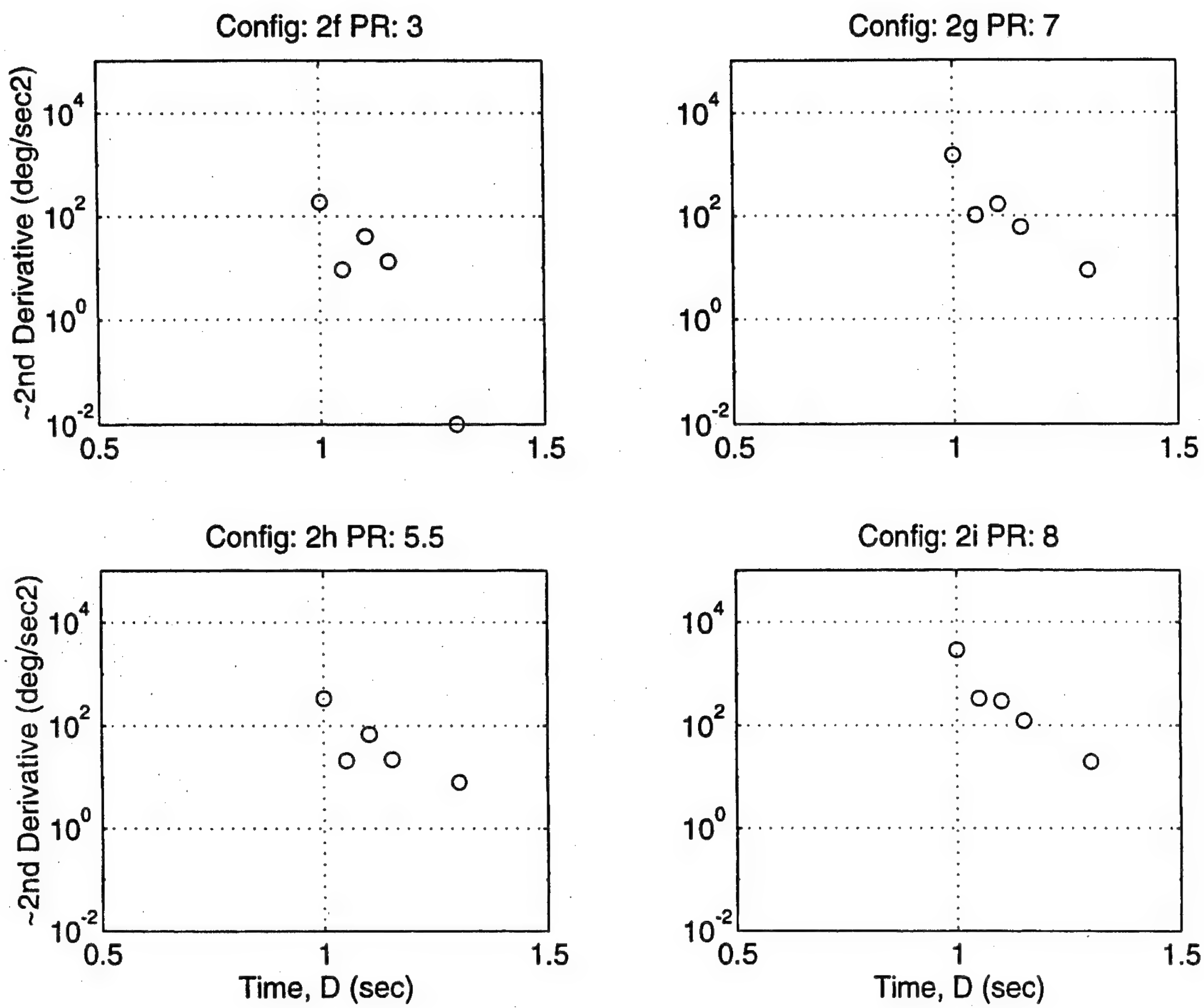

Config: 8-4-6 PR: 1
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5

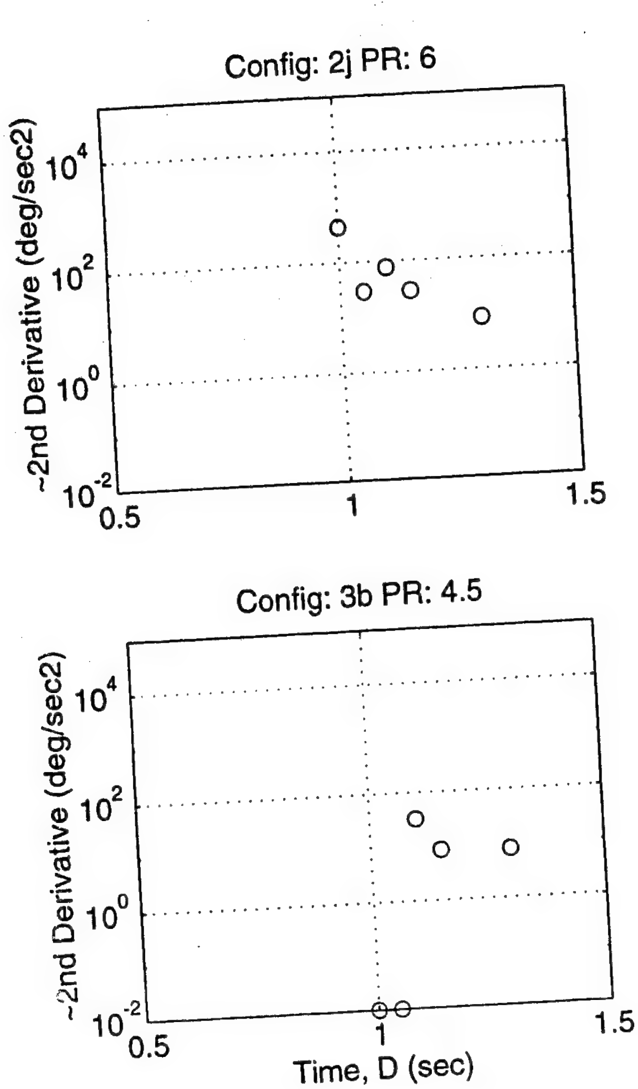

Config: 1a PR: 5
Config: 1b PR: 3.25
Config: 1c PR: 4
Config: 1d PR: 4.25
~2nd Derivative (deg/sec2)
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)
Time, D (sec)

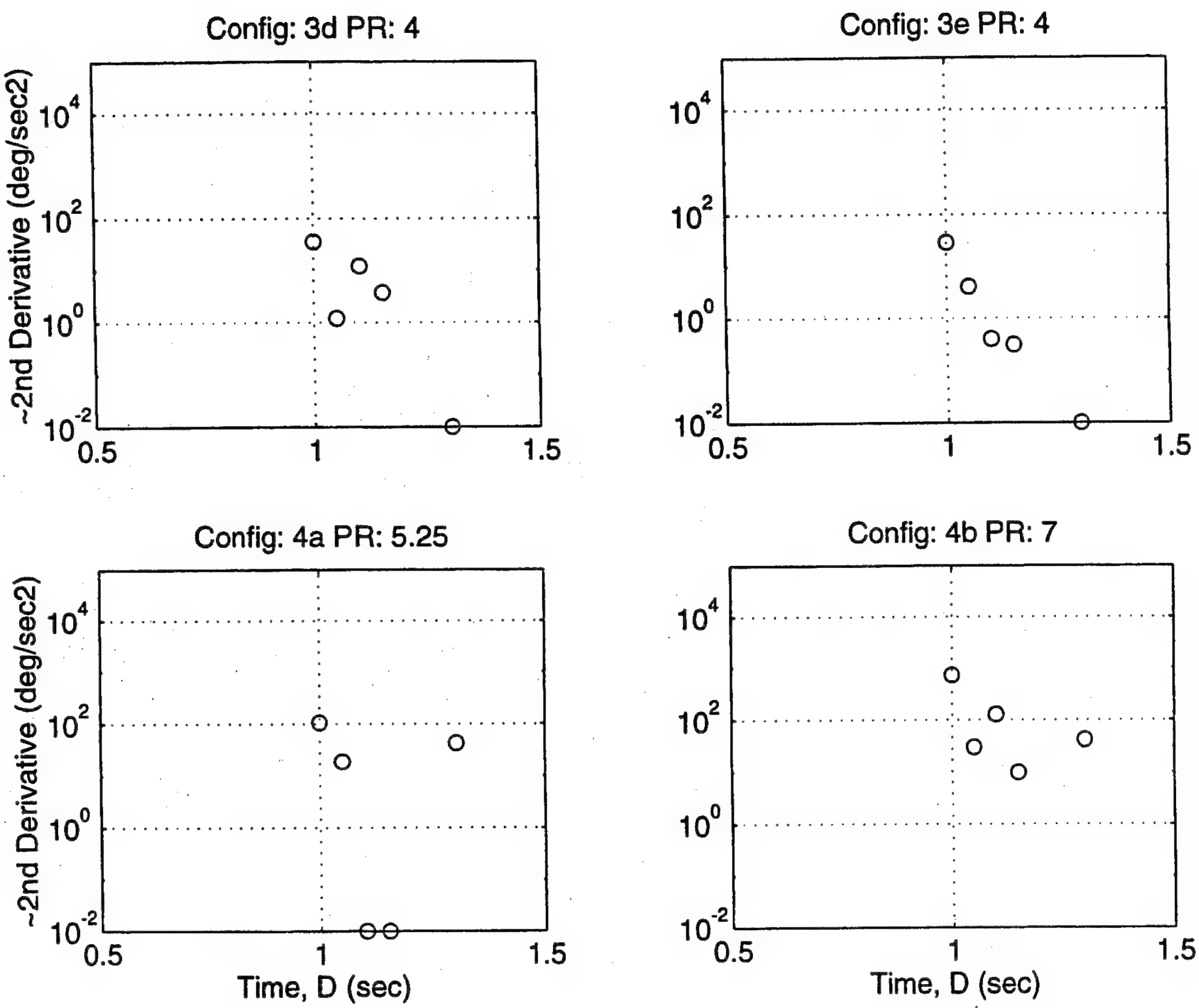


Config: 1e PR: 6
Config: 1f PR: 8
Config: 1g PR: 8.5
Config: 2a PR: 4.25
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5
Time, D (sec)

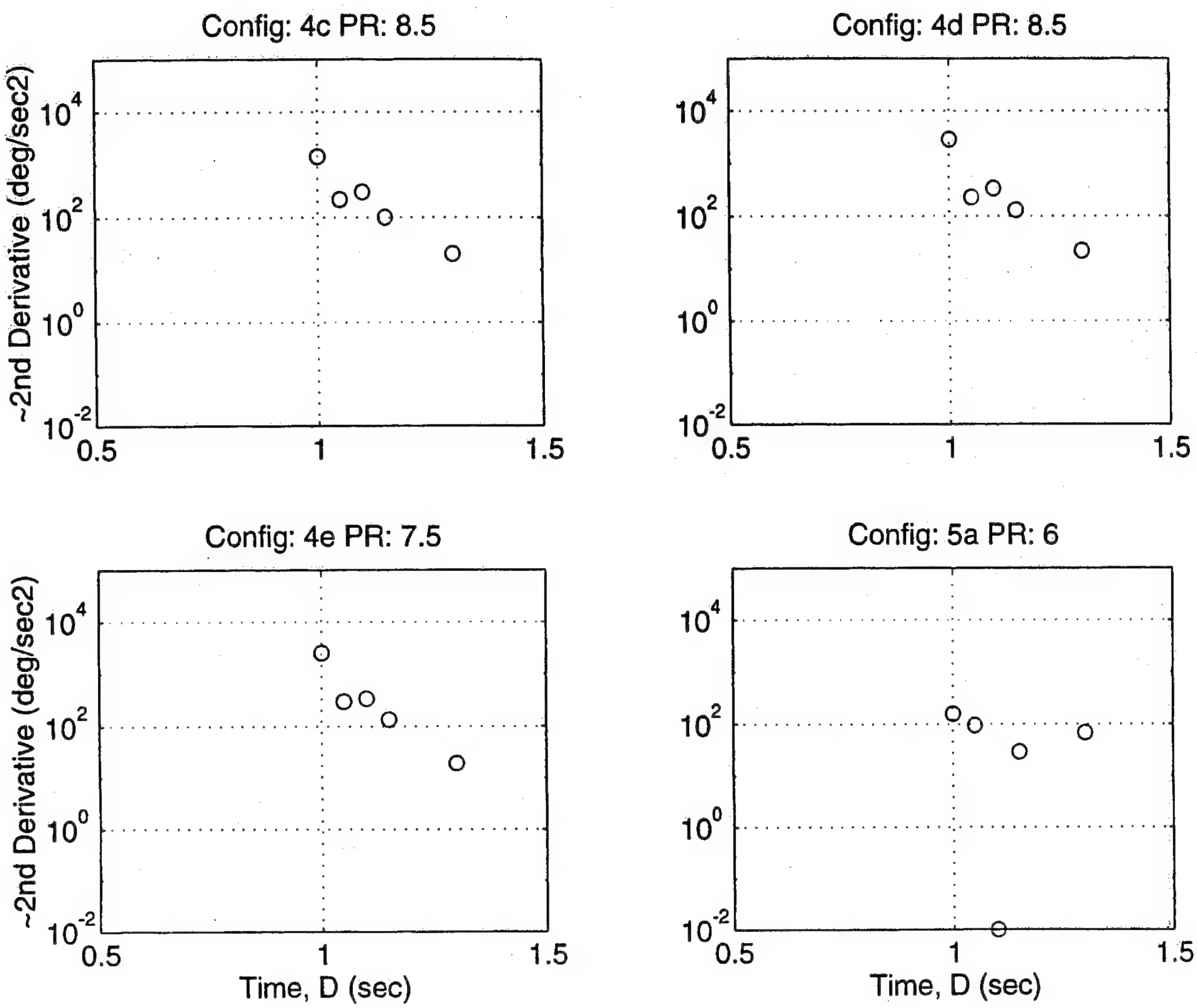

Config: 2b PR: 5.5
Config: 2c PR: 3
Config: 2d PR: 2.5
Config: 2e PR: 4
~2nd Derivative (deg/sec2)
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)
Time, D (sec)

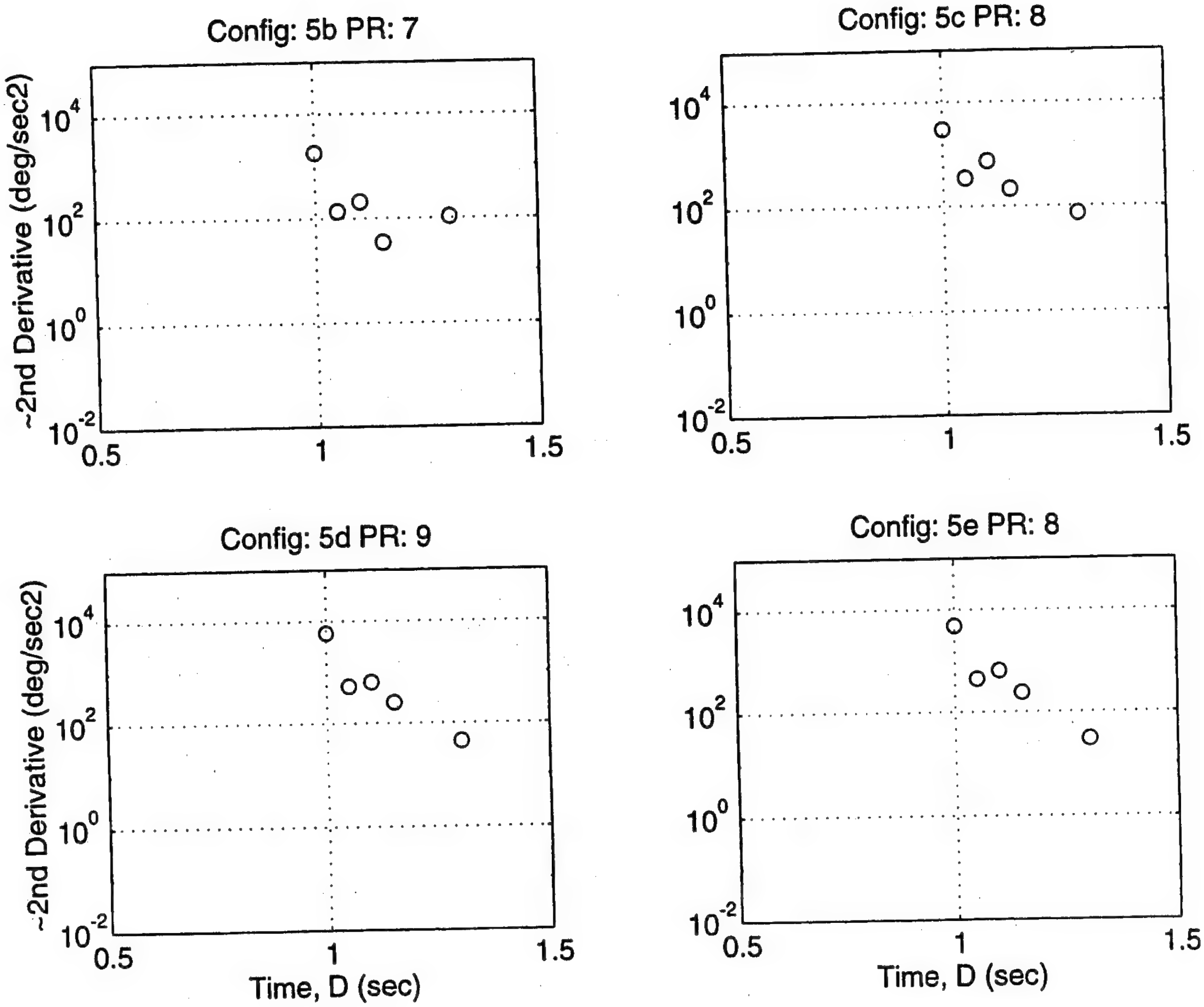

Config: 2f PR: 3
Config: 2g PR: 7
Config: 2h PR: 5.5
Config: 2i PR: 8
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)


Config: 2j PR: 6
Config: 3a PR: 4
Config: 3b PR: 4.5
Config: 3c PR: 3.5
~2nd Derivative (deg/sec2)
Time, D (sec)
10^4
10^2
10^0
10^-2
0.5
1
1.5

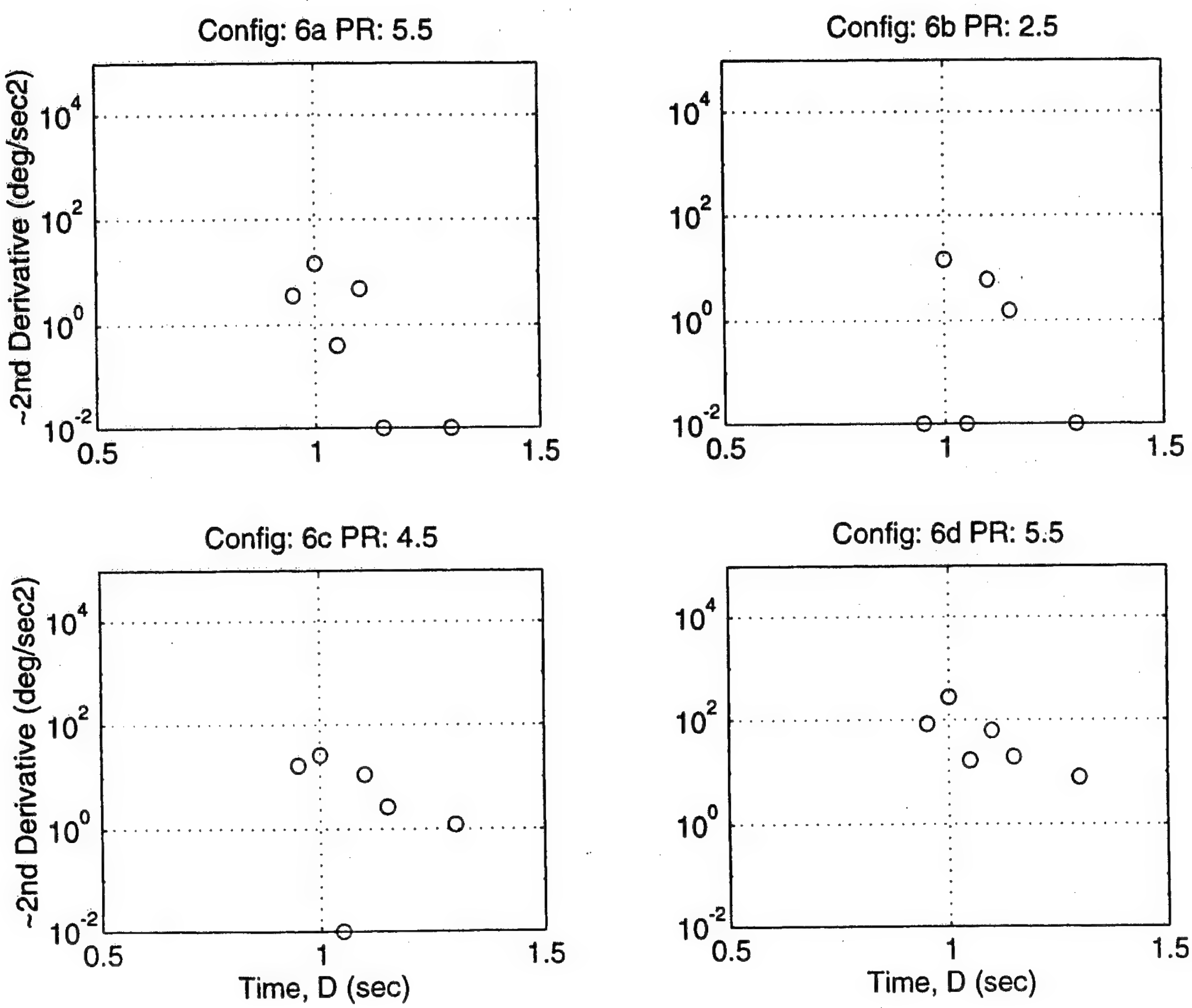


Config: 3d PR: 4
Config: 3e PR: 4
Config: 4a PR: 5.25
Config: 4b PR: 7
~2nd Derivative (deg/sec2)
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)
Time, D (sec)

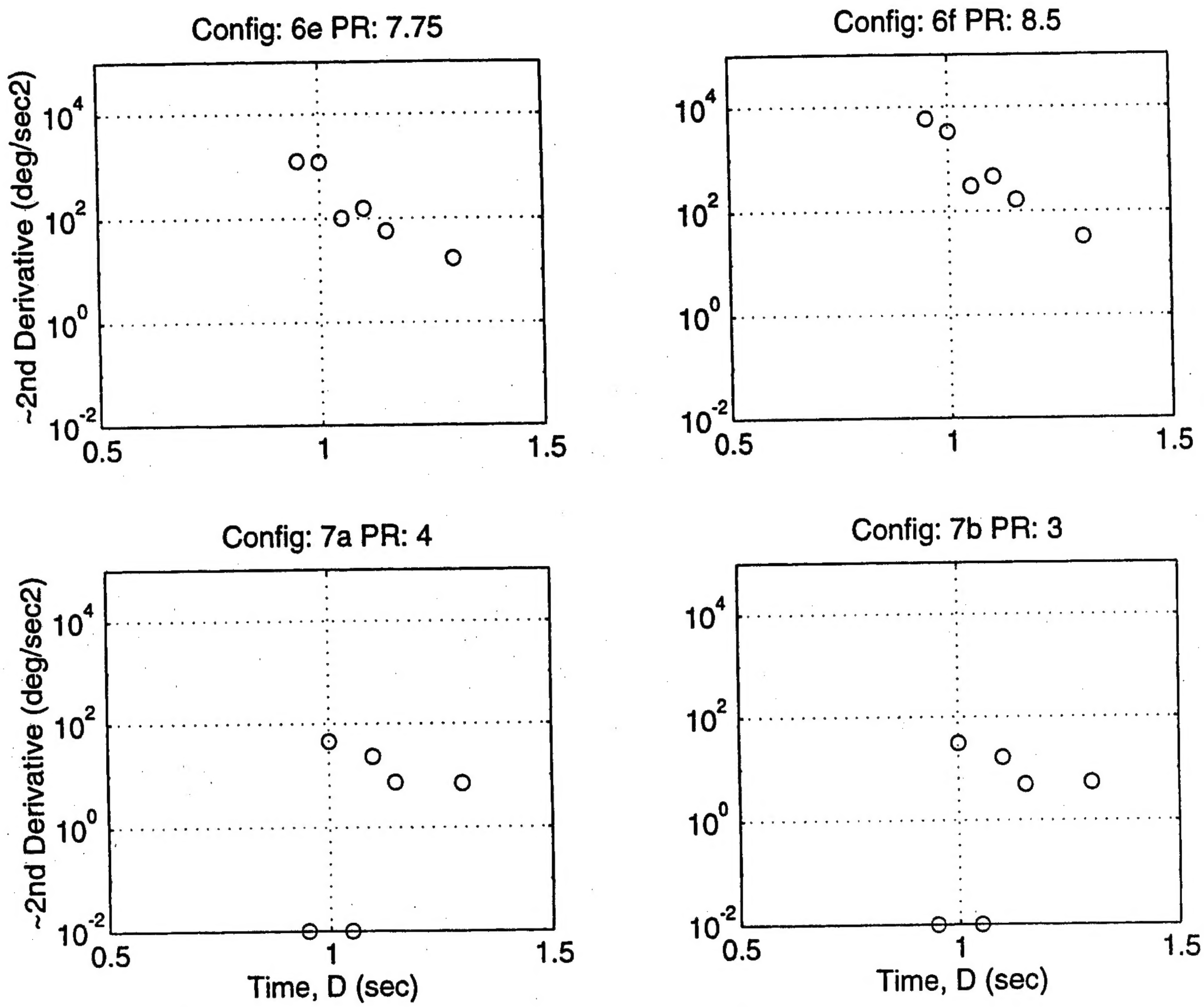

Config: 4c PR: 8.5
Config: 4d PR: 8.5
Config: 4e PR: 7.5
Config: 5a PR: 6
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5
Time, D (sec)



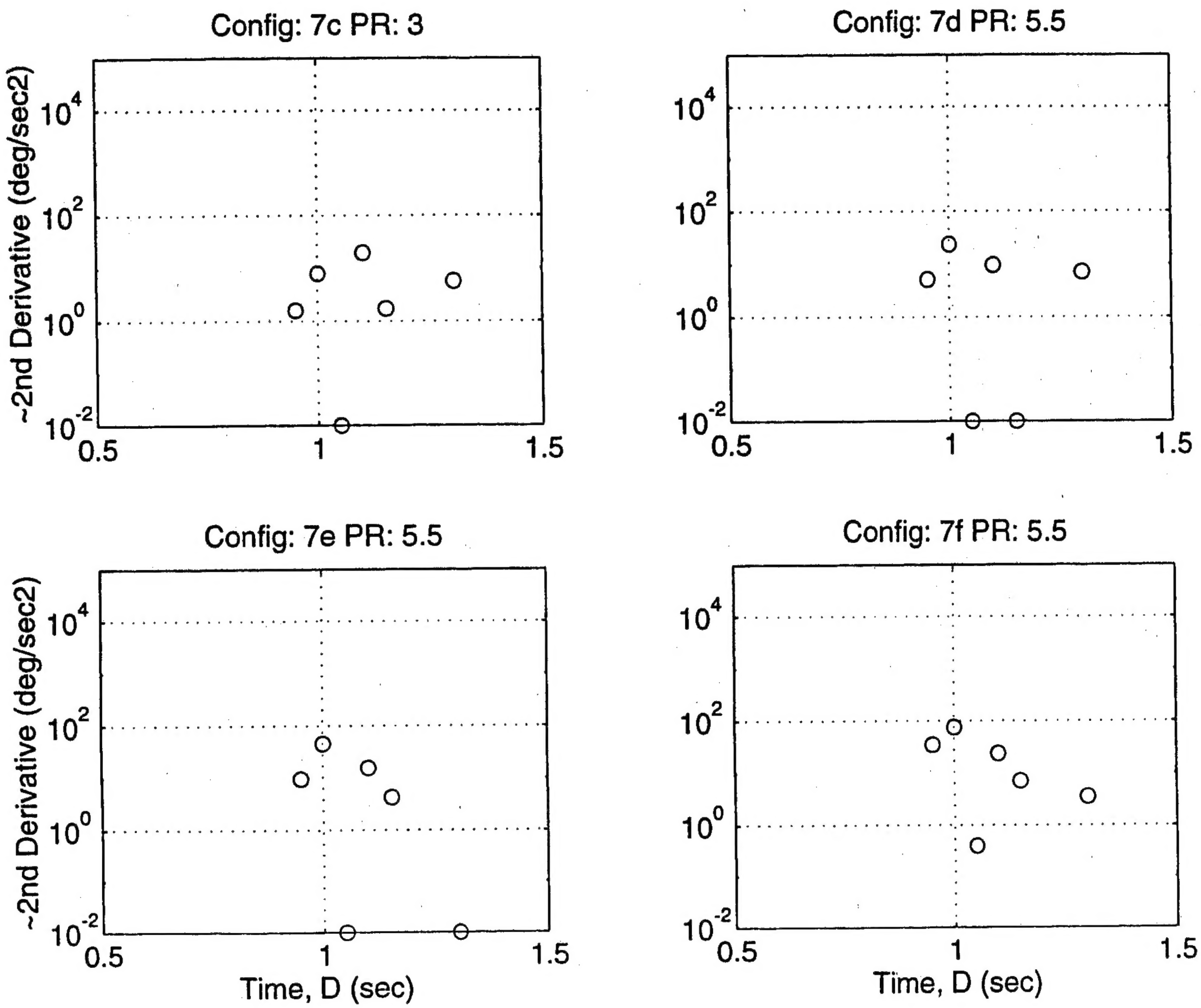
Config: 5b PR: 7
Config: 5c PR: 8
Config: 5d PR: 9
Config: 5e PR: 8
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5
Time, D (sec)

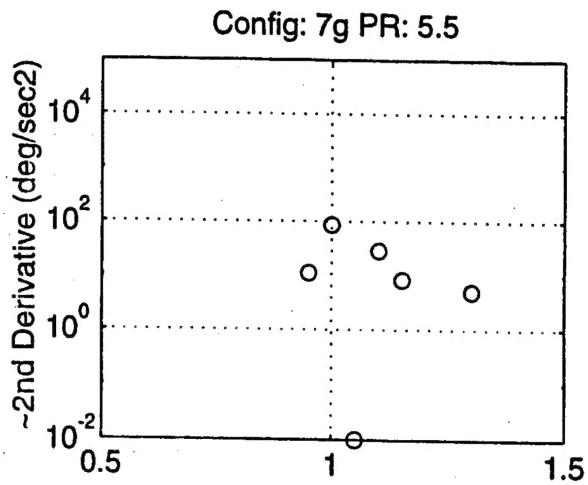


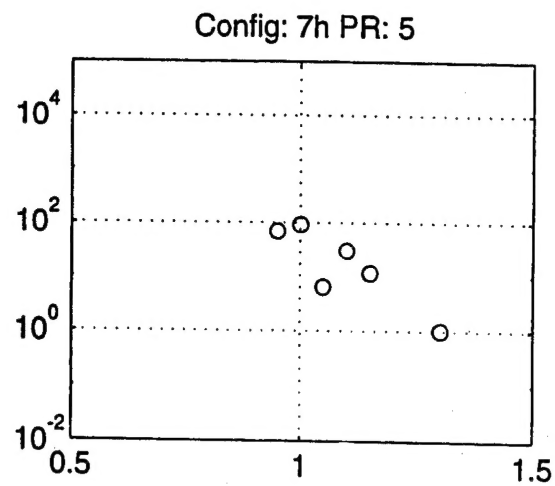
Config: 6a PR: 5.5
Config: 6b PR: 2.5
Config: 6c PR: 4.5
Config: 6d PR: 5.5
~2nd Derivative (deg/sec2)
Time, D (sec)

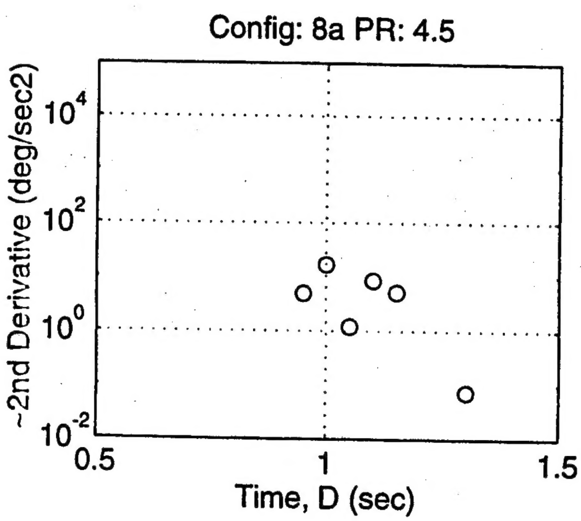


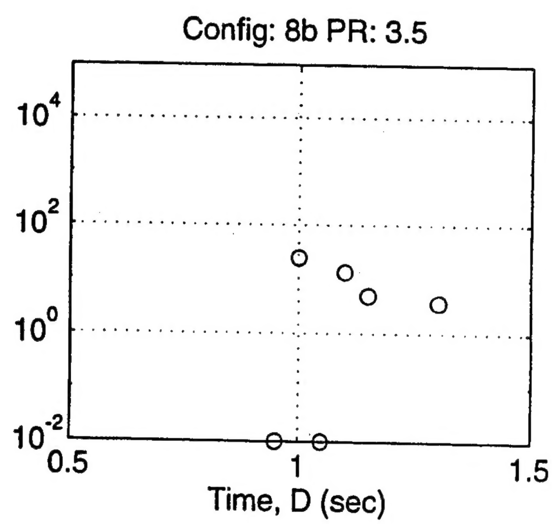
Config: 6e PR: 7.75
Config: 6f PR: 8.5
Config: 7a PR: 4
Config: 7b PR: 3
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5
Time, D (sec)

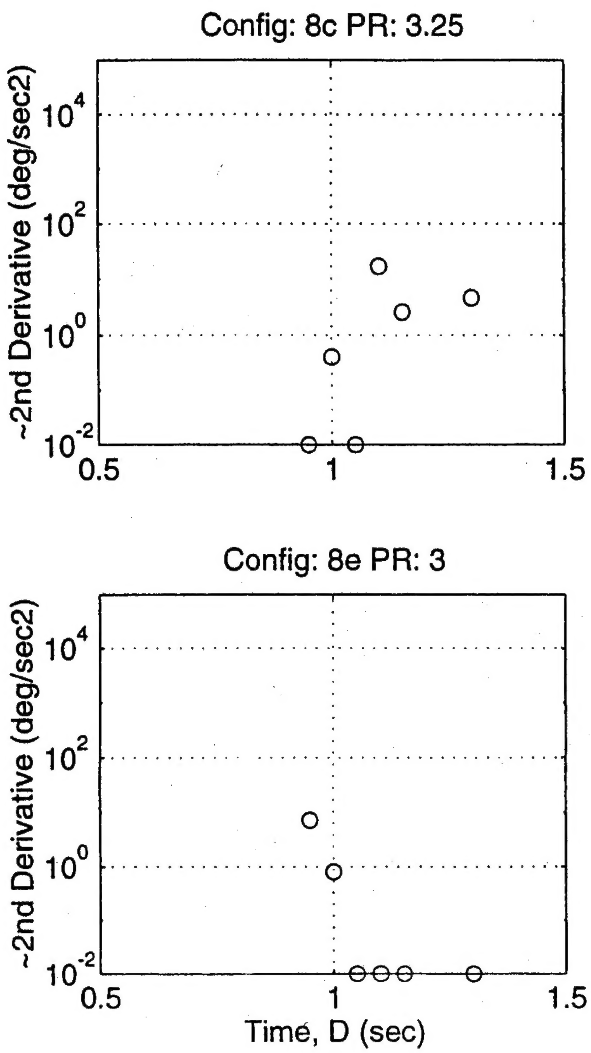

Config: 7c PR: 3
Config: 7d PR: 5.5
Config: 7e PR: 5.5
Config: 7f PR: 5.5
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)


Config: 7g PR: 5.5
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5


Config: 7h PR: 5
10^4
10^2
10^0
10^-2
0.5
1
1.5


Config: 8a PR: 4.5
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^-2
0.5
1
1.5
Time, D (sec)


Config: 8b PR: 3.5
10^4
10^2
10^0
10^-2
0.5
1
1.5
Time, D (sec)


Config: 8c PR: 3.25
Config: 8d PR: 3
Config: 8e PR: 3
~2nd Derivative (deg/sec2)
10^4
10^2
10^0
10^{-2}
0.5
1
1.5
Time, D (sec)